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PATENT  
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- ☐ NEW PATENT APPLICATION  
☐ CONTINUATION  
☐ DIVISIONAL  
☒ CONTINUATION-IN-PART  
☐ CONTINUED PROSECUTION APPLICATION

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*Janice Pampell*  
Janice Pampell

Assistant Commissioner  
for Patents  
Washington, D.C. 20231

Sir:

Transmitted herewith for filing is the Continuation-In-Part patent application of:

Inventor: Daniel N. Miller, et al.

For: METHOD AND APPARATUS OF ASYMMETRIC INJECTION INTO SUBSONIC FLOW OF A HIGH ASPECT RATIO/COMPLEX GEOMETRY NOZZLE

Date Filed: July 21, 2000

Enclosed are:

1. ☒ 46 pages of the Specification, 30 claims, 1 page of Abstract
2. ☒ 11 sheets of informal drawings
3. ☐ Assent of Assignee to Reissue
4. ☐ A Reissue Declaration by Inventors and Power of Attorney
5. ☐ Request for Abstract of Title and Offer to Surrender

Full name of first inventor	Daniel N. Miller
Citizenship	United States of America
Post Office Address	3252 Webash Avenue, Fort Worth, Texas 76109

6. ☐ Cancel in this application original claims:
7. ☐ A preliminary amendment is enclosed.



25094

PATENT TRADEMARK OFFICE

The filing fee has been calculated as shown below:

CLAIMS	FOR	NUMBER FILED	ALLOWED	NUMBER EXTRA	RATE	CALCULATIONS
	TOTAL CLAIMS (37 C.F.R. § 1.16(c) or (j))	30	20	10	x18	\$ 180.00
	INDEPENDENT CLAIMS (37 C.F.R. § 1.16(b) or (i))	2	3	0	x 78	\$ 0
				BASIC FEE Large Entity \$690.00		\$ 690.00
				BASIC FEE Small Entity \$345.00		0
	* Reissue claims in excess of 20 and over original patent ** Reissue independent claims over original patent			TOTAL =		\$870.00

8. ☐ Please charge my Deposit Account No. 50-0456 the amount of \$
9. ☒ The Assistant Commissioner is hereby authorized to charge *any deficiency or credit any overpayment* to Deposit Account No. 50-0456.
- Any additional filing fees required under 37 C.F.R. 1.16.
  - Any patent application processing fees under 37 C.F.R. 1.17.
10. ☒ Amend the specification by inserting before the first paragraph on page 1:
- This application claims the benefit of U.S. Patent Application No. 08/906,731 filed on August 5, 1997 entitled "Method and Apparatus of Pulsed Injection for Improved Nozzle Flow Control." Additionally, this application claims priority to and repeats a substantial portion of prior application entitled "Method and Apparatus of Pulsed Injection for Improved Nozzle Flow Control" filed on August 5, 1997 which was accorded serial number 08/906,731. Since this application names an inventor named in the prior application, the application constitutes a continuation in part of the prior application. This application incorporates by reference prior U.S. Patent Application No. 08/906,731 filed on August 5, 1997 entitled "Method and Apparatus of Pulsed Injection for Improved Nozzle Flow Control" and U.S. Patent Application No. 08/906,768 filed on August 5, 1997 entitled "Method and Apparatus of Asymmetric Injection at the Subsonic Portion of a Nozzle Flow" which is herein incorporated by reference.*
11. ☐ A verified statement claiming small entity status was filed \_\_\_\_\_ in parent application Serial No. \_\_\_\_\_, filed \_\_\_\_\_, and such status is still proper.
12. ☒ The prior application is assigned to Lockheed Martin Corporation. *However, a new Assignment is enclosed since new inventors are listed.*
13. ☐ Please transfer the drawings from the prior application to the new application.
14. ☐ A true copy of the prior application as filed is enclosed, including the Power of Attorney filed in the parent application.

15. ☒ Information Disclosure Statement(s) filed in the prior application under 37 C.F.R. § 1.97 is(are) hereby made of record, (copy of 1449 is enclosed herewith).
16. ☒ A new Declaration and Power of Attorney is submitted because new inventors were added to this application
17. ☒ Check enclosed in the amount of \$870.00 representing the appropriate filing fee.

Address all future communications to:

William N. Hulsey III  
GRAY CARY WARE ▲ FREIDENRICH LLP  
100 Congress Avenue, Suite 1440  
Austin, Texas 78701  
Telephone: 512-457-7040  
Facsimile: 512-457-7070

Respectfully submitted,



William N. Hulsey III  
Reg. No. 33,402  
Attorney for Applicant

Dated: July 21, 2000

GRAY CARY WARE ▲ FREIDENRICH LLP  
100 Congress Avenue, Suite 1440  
Austin, Texas 78701  
Telephone: 512-457-7040  
Facsimile: 512-457-7070

IN THE UNITED STATES PATENT AND TRADEMARK OFFICE

In the Application of: Daniel N. Miller, et al.  
Date Filed: July 21, 2000  
Title: METHOD AND APPARATUS OF ASYMMETRIC INJECTION INTO  
SUBSONIC FLOW OF A HIGH ASPECT RATIO/COMPLEX  
GEOMETRY NOZZLE

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Dear Sir:

**CERTIFICATE OF MAILING BY EXPRESS MAIL**

I hereby certify that the attached Transmittal Form, Continuation-in-Part Patent Application, Declaration and Power of Attorney, Informal Drawings, Information Disclosure Statement and PTO 1449, appropriate filing fee, and postcard are being deposited with the United States Postal Service "Express Mail Post Office to Addressee" service under 37 C.F.R. 1.10 on this 21<sup>st</sup> day of July, 2000 and is addressed to the Assistant Commissioner of Patents, Washington, D.C. 20231 Attn: Box Patent Applications.

  
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METHOD AND APPARATUS OF ASYMMETRIC INJECTION  
INTO SUBSONIC FLOW OF A HIGH ASPECT  
RATIO/COMPLEX GEOMETRY NOZZLE

RELATED APPLICATIONS

This application claims the benefit of U.S. Patent Application No. 08/906,731 filed on August 5, 1997 entitled "Method and Apparatus of Pulsed Injection for Improved Nozzle Flow Control." Additionally, this application claims priority to and repeats a substantial portion of prior application entitled "Method and Apparatus of Pulsed Injection for Improved Nozzle Flow Control" filed on August 5, 1997 which was accorded serial number 08/906,731. Since this application names the inventor named in the prior application, the application constitutes a continuation in part of the prior application. This application incorporates by reference prior U.S. Patent Application No. 08/906,731 filed on August 5, 1997 entitled "Method and Apparatus of Pulsed Injection for Improved Nozzle Flow Control" and U.S. Patent Application No. 08/906,768 filed on August 5, 1997 entitled "Method and Apparatus of Asymmetric Injection at the Subsonic Portion of a Nozzle Flow" which is herein incorporated by reference.

TECHNICAL FIELD OF THE INVENTION

5 This invention relates in general to the field of  
nozzles for controlling a fluid flow, and more  
particularly, to a nozzle for throttling and vectoring  
a fluid flow, such as the exhaust flow exiting a jet  
engine, through the throat of the nozzle by varying the  
effective cross-sectional area of the throat with the  
injection of a steady, unsteady, or pulsed secondary  
flow.

BACKGROUND OF THE INVENTION

Jet engines create thrust by directing a high energy exhaust stream from an exhaust nozzle. Typically, a jet engine accepts air through an inlet and compresses the air in a compressor section. The compressed air is directed to a combustion chamber, mixed with fuel, and burned. Energy released from the burning fuel creates a high temperature in the combustion chamber. The hot, high-pressure air passes through a turbine section and into an exhaust chamber. The high pressure air is then forced from the exhaust chamber through a nozzle, where the air exits the engine. Typically, as the air passes through the throat of the nozzle, it expands and accelerates from subsonic to supersonic speeds, essentially translating the energy of the exhaust flow from a pressure into a velocity. The energy level of the air in the exhaust chamber generally relates to the velocity of the air as it exits the nozzle. The greater the velocity of a given mass flow of air exiting an engine, the greater the thrust created by the engine.

Military aircraft commonly augment the energy level of the air in the exhaust chamber by using an afterburner. Afterburners add fuel to the exhaust chamber and ignite the fuel in the exhaust chamber, which increases the temperature of the exhaust flow. Although the energy added by afterburned fuel can greatly increase the thrust of the engine, the reduced density of the hotter air requires a larger nozzle effective throat area. Failure to increase nozzle

effective area during afterburning with a typical jet engine can cause excessive back pressure in the compressor section and turbine section, causing the engine to stall.

5           To alleviate these difficulties, jet engines with afterburners typically use variable geometry nozzles to throttle the exhaust flow from the exhaust chamber. When afterburner is initiated, the circumference of the nozzle's throat is increased to increase the cross-  
10       sectional flow area through the throat. This increased cross-sectional area allows air to more easily escape from the exhaust chamber. Modern afterburning jet engines with variable geometry nozzles can require as much as a two-fold increase in cross-sectional throat  
15       area to maintain constant engine flow and back pressure in response to the extra thermal energy added by afterburning.

          Although variable geometry nozzles allow the use of afterburner, they also have many inherent  
20       disadvantages which penalize aircraft performance. For instance, a variable geometry nozzle can make up a significant portion of the weight of an engine. Such nozzles are typically made of large, heavy metal flaps which mechanically alter nozzle geometry by diverting  
25       exhaust flow with physical blockage, and thus have to endure the high temperatures and pressures associated with exhaust gases. In the iris-type nozzles typically used on afterburner-equipped engines, the actuators used to adjust the nozzle flaps to appropriate  
30       positions in the exhaust flow tend to be heavy,



expensive and complex because of the forces presented by the exhaust flow which the nozzle flaps must overcome. Further, the nozzle flaps typically constrict the exhaust flow by closing and overlapping each other, which allows hot air to escape between the flaps. These leaks cause reductions in thrust. Variable geometry nozzles are also difficult to implement on exotic nozzle aperture shapes typical of advanced tactical fighter aircraft.

Attempts to reduce the disadvantages of variable geometry nozzles have had limited success. The state-of-the-art tactical aircraft is the Lockheed F-22 Raptor. The Raptor employs a two-dimensional variable geometry nozzle that can vector or turn the exhaust flow of the Raptor's engine to provide directional thrust control. Although the two-dimensional nozzle flaps of the Raptor provide better infrared and radar cross section characteristics than can be obtained from typical iris-type nozzles, even the Raptor's advanced system suffers from the above-mentioned disadvantages. For instance, air can leak along the intersection of the two-dimensional nozzle flaps, introducing inefficiency.

Attempts to use a fixed geometry nozzle with afterburning engines have met with only limited success due to the difficulty of maintaining flow through the engine when an overpressure is created by afterburner initiation. For instance, U.S. Patent No. 5,406,787 issued to Terrier uses an additional compression stage to vary pressure during engine operation and

afterburning to counteract temperature variations created by the afterburner in the exhaust chamber. However, this system requires modification to the engine and other complexities such as a control program to monitor and adjust pressure produced by the compression section.

Another method for using a fixed geometry nozzle with a jet engine is to inject a secondary flow of high pressure air across the primary flow as the primary flow passes through the nozzle, as is explained in "Conceptual Development of Fixed-Geometry Nozzles Using Fluidic Injection for Throat Area Control" AIAA-95-2603 and "A Static Investigation of Fixed-Geometry Nozzles Using Fluidic Injection for Throat Area Control" by J.A. Catt and D.N. Miller, AIAA-95-2604, July 1995. The secondary flow can partially block the exhaust exiting through the nozzle to decrease the flow through the nozzle when needed to increase the pressure within the exhaust chamber. When an overpressure exists in the exhaust chamber, the secondary flow can be reduced or eliminated to increase the flow through the nozzle.

Although the injection of a secondary flow will support a fixed geometry nozzle in an afterburning jet engine, this method also introduces inefficiencies to the engine's operation. For instance, the amount of afterburning may be limited due to the lower effectiveness of secondary injection compared to the effectiveness of variable geometry nozzles. Also, injection of air across the flow of the exhaust tends to use a large amount of high pressure air to obtain

effective nozzle blockage. Thus, injection can introduce inefficiency because the total momentum of the exhaust flow is decreased by the decreased flow from the compressor section into the combustion section if compressed air is bled from the compressor section for injection. This inefficiency can result in a reduced range of operations for a given fuel supply and a fuel flow.

SUMMARY OF THE INVENTION

Therefore, a need has arisen for a method and apparatus that efficiently controls the flow through a nozzle by introducing a secondary fluidic flow to the flow field through the nozzle, the secondary flow providing a maximum amount of blockage to the flow field through the nozzle with a minimal injection mass flow. In accordance with the present invention, a steady, unsteady or pulsed flow is injected proximate to a nozzle opening and across the flow field to substantially eliminate or reduce disadvantages and problems associated with previously developed variable geometry and fixed geometry nozzles.

A method and apparatus are provided for throttling and vectoring the primary jet nozzle by partially blocking the nozzle with a steady, unsteady or pulsed flow across the flow field through the opening of the nozzle. A fluidic flow field is defined in a flow container that directs a pressurized, fluidic flow from the container towards an exit of the container. A nozzle cooperates with the exit of the flow container to control the fluidic flow as it exits the flow container. One or more injectors associated with the nozzle proximate to the nozzle's throat and downstream of the throat can introduce a steady, unsteady or pulsed fluidic flow that interacts with the primary fluidic flow. A controller associated with the injectors directs the injectors to provide the steady, unsteady or pulsed fluidic flow having a predetermined frequency, amplitude or waveform, as needed to achieve

a desired partial blockage of the nozzle, thereby  
skewing the sonic plane of the nozzle and vectoring the  
jet. The controller can select a frequency, amplitude  
or waveform for the pulsed secondary flow so that the  
5 effective cross sectional area of the nozzle adjusts  
the pressure within the flow container to predetermined  
values by controlling or throttling the mass flow  
characteristics of the primary flow through the nozzle,  
including the primary flow's mass, velocity, pressure,  
10 temperature and density.

More specifically, in one embodiment, a fixed  
geometry nozzle is coupled to the exhaust chamber of a  
jet engine. The nozzle has a throat leading to a  
divergent area, the divergent area having a low  
15 expansion ratio. A plurality of injectors, each of  
which can be formed as a slot, are incorporated  
proximate to the throat of the nozzle, and downstream  
of the throat and directionally opposed to the subsonic  
portion of the exhaust flow through the engine. Each  
20 injector is oriented to direct injected flow into the  
flow field of the exhaust gas through the nozzle to  
optimize throttling or vectoring of the primary fluid  
flow. For instance, an injector can inject a pulse of  
fluid at an upstream angle relative to the flow field,  
25 such as an angle between zero and thirty degrees  
opposed to the primary flow, which travels along a  
longitudinal axis through the nozzle. Opposing  
injectors or slots injecting similar opposing flows can  
provide symmetric blockage of the nozzle's opening to  
30 reduce nozzle effective throat area and control the

primary flow through the nozzle without changing the  
vector angle of the primary flow, thus throttling the  
engine. Injection of a secondary flow from a single  
injector can provide an asymmetric blockage of the  
nozzle's opening to change the vector angle of the  
primary flow. An asymmetric secondary flow from  
opposing injectors can provide both throttling and  
vectoring of the primary flow.

A source of high pressure air is provided to each  
injector, either from the compression section of the  
engine or from another convenient source, such as a  
separate compressor. The high pressure air is injected  
into the flow field in pulses by either a mechanical  
valve or an acoustic vibrator, such as a piezoelectric  
device. The frequency, amplitude and waveform of the  
pulse varies according to the amount of blockage  
desired at the nozzle. In one embodiment, each  
injector may rotate relative to the nozzle to provide  
a secondary flow at different angles relative to the  
flow field. In another embodiment, the injected flow  
can include fuel which can be ignited to enhance  
blockage of the flow field. In another embodiment, the  
flow field from the engine can be vectored or  
redirected by applying asymmetric injection at the  
nozzle. Asymmetric injection can be provided by  
injecting different mass flow rates from each of a  
plurality of injectors, or by altering the pulse  
frequency, amplitude or waveform at each such injector.  
Similarly, asymmetry can be imposed by using different

injection angles or different fuel flows for each injector.

The present invention provides many technical advantages over previously developed apparatus and methods for controlling a flow through a nozzle to allow throttling of an engine or vectoring of an engine's thrust. Pulsed injection, when used instead of or in combination with a variable geometry nozzle, can reduce the weight, cost, and complexity of a nozzle. A pulsed injection system reduces the weight of a nozzle by eliminating or limiting the need for durable heavy moving parts such as hinges, seals, actuators, hydraulics and other mechanical items necessary to open and close the typical iris type variable geometry nozzle.

Another technical advantage of the present invention is that an aircraft equipped with an engine and fixed-geometry nozzle using pulsed injection can be implemented to non-circular exhaust aperture shapes typical of advanced fighter concepts. These aperture shapes, such as elliptical or diamond shapes, allow for better blending and integration into the aircraft aft body structure than typical iris-type nozzles.

Another technical advantage of the present invention, particularly when a fixed geometry nozzle is used, is that alternative materials can be used for the nozzle structure with an eye towards thermal rather than mechanical constraints. For instance, ceramic materials can form a fixed nozzle supported directly by the structure of the aircraft. Such ceramic materials

can provide a heavy duty heat resistance nozzle structure with much improved durability compared to conventional metal and carbon materials. The reduced complexity of such a fixed nozzle system will reduce the cost of operating and maintaining the aircraft and can increase the efficiency of operating the aircraft due to the significantly reduced weight of such a system. Further, a nozzle incorporated with the aircraft's structure can be shaped to minimize drag, thus increasing the aircraft's efficiency and range.

Another technical advantage of the present invention is that an asymmetric secondary flow can provide vectoring of an engine's thrust. Thrust vectoring can allow aircraft control of pitch and yaw at all flying speeds, and can decrease the surface area of control surfaces, resulting in reduced aircraft drag and weight.

Another technical advantage of the present invention is that a fixed geometry nozzle can provide a combination of throttling and vectoring functions. Opposing injectors can provide throttling with nozzle blockage according to their combined mass flow and pulsing characteristics while also providing vectoring by varying the distribution of the total secondary flow between the injectors.

The pulsed injection system of the present invention offers additional technical advantages over previously developed injection techniques. Pulsed or unsteady injection of a fluidic secondary flow can provide improved penetration into the fluidic flow



compared to the penetration provided by steady state injection. This increased penetration enhances the blockage of the nozzle opening without increasing the time averaged mass flow of the injected secondary flow.

5 Thus, the effective cross sectional area of a nozzle and its vectoring angle can be controlled with less overall fluidic secondary flow injection. This increases the efficiency of the engine since less compressed air is needed by a pulsed secondary flow

10 compared to a steady state secondary flow, and also decreases the size of the ducts needed to provide air to the injectors.

BRIEF DESCRIPTION OF THE DRAWINGS

A more complete understanding of the present invention and advantages thereof may be acquired by referring to the following description taken in  
5 conjunction with the accompanying drawings in which like reference numbers indicate like features and wherein:

FIGURES 1A - 1C depict one embodiment of the present invention;

10 FIGURES 2A and 2B provide An ultra high aspect ratio nozzle of the present invention;

FIGURES 3A - 3C provide a more detailed depiction of an ultra high aspect ratio nozzle of the present invention;

15 FIGURES 4A and 4B depict a nozzle with an arrowhead shaped trailing edge;

FIGURES 5A - 5E provide an additional depiction of an embodiment of the present invention with preferred injector design vector angles;

20 FIGURE 6 illustrates the performance envelope of a fluidically controlled nozzle;

FIGURE 7 depicts a flow diagram for the development process associated with the present invention ;

25 FIGURE 8 depicts an experimental apparatus for pulsed injection nozzle flow control;

FIGURE 9 depicts a side sectional view of jet engine equipped with pulsed injection nozzle flow control;

FIGURE 10 depicts a side sectional view of injectors incorporated in a nozzle;

FIGURE 11 depicts a perspective sectional view of a nozzle having slot injectors incorporated at its throat; and

FIGURE 12 depicts a side sectional view of a nozzle providing asymmetric injection to vector an exhaust flow.

FIGURE 10 depicts a side sectional view of injectors incorporated in a nozzle;

DETAILED DESCRIPTION OF THE INVENTION

Preferred embodiments of the present invention are illustrated in the FIGURES, like numerals being used to refer to like and corresponding parts of the various drawings.

5 The present invention reveals a method and apparatus for controlling the effective area and thrust vector angle of a fluid flow. In one embodiment, the fluid flow is controlled in an advanced, high aspect ratio, complex aperture geometry nozzle using  
10 asymmetric injection into the subsonic portion of the fluid flow.

Fluidics alter the mass flow and direction of a main fluid stream, or primary fluid flow, by the  
15 introduction of small control jets. Small disturbances created by injectors at points along the primary fluid flow produce large responses in the main stream. Fluidic injection is used to provide internal flowpath shape variation for jet control in nozzles and holds  
20 the promise of reducing the weight and complexity of future exhaust systems by eliminating mechanical flowpath actuation. By introducing an injector into the exhaust stream near the throat or exit, the injector plume can produce a stable fluidic  
25 obstruction. By metering injector flow, the size of the obstruction, and hence, the internal flowpath shape can be actively modified to control both jet area and thrust vector angle. In one embodiment of the present  
30 primary flow can take unconventional shapes and

injectors can be used to manipulate effective sonic planes for throttling, controlling, and vectoring the primary flow. These shapes are not limited by mechanization concerns as are conventional variable geometry nozzles. Thus allowing the structure to be optimized for non-fluidic concerns such as observability (radar and IR signatures) and material composition.

While functionally easy to describe, fluidics' performance is dictated by complex interactions among approximately two dozen geometric and fluid properties.

In the propulsion area of high performance aircraft, the multi-function exhaust nozzles may account for 30 percent of the total engine weight. Weight is reduced or eliminated by removing the actuation systems and moving surfaces associated with variable geometry exhaust systems. Fluidics allow this without losing afterburning or thrust vectoring functionality.

Eliminating moving parts reduces parts count, increases reliability, and potentially removes 30 to 50 percent from the exhaust system cost. In addition, a fixed nozzle can be easily shaped for reduced drag and signature, with the latter yielding significant stealth benefits.

Furthermore, fixed nozzles can be fabricated from a wider range of materials. This allows one of the most replaced items on fighter aircraft, the nozzle internal flap (the area between the exhaust nozzle

throat and exit) to be designed based on thermal rather than mechanical constraints.

Turbofan engine features, such as thrust vectoring and afterburning, require complex controls for  
5 manipulating exhaust angle and exhaust nozzle geometry. During afterburning, fuel is sprayed directly into the exhaust duct. Afterburning dramatically increases thrust as well as exhaust temperature. To maintain constant flow and backpressure, the exhaust nozzle  
10 throat area must increase 50 to 100 percent over its normal cruise operation size.

This thrust vectoring and afterburning control system is a complex mechanical maze of hundreds of parts - hinges, seals, hydraulic actuators, bearings,  
15 flaps, etc. - that must slide, pivot, extend, and retract while maintaining tight tolerances under extreme temperature and pressure variations.

In a fluidic nozzle, effective throat area is controlled via small injectors symmetrically located  
20 around the nozzle throat. Depending on the configuration, injection angle, flow rate and pressure, these injectors can throttle the main exhaust stream as much as 50 percent between afterburning and normal cruise operation.

25 Thrust vectoring is a technique for turning an aircraft by diverting the exhaust stream using movable flaps or paddles. In fluidic thrust vectoring, a second set of injectors is located around the nozzle flap, but the injectors are individually activated, as

needed, to skew the sonic plane, the section of the exhaust where the flow reaches a speed of Mach 1.

Control flows for throttling and vectoring may be bled from the compressor stage or some other high-  
5 pressure source in the engine.

The present invention represents an improvement over known prior art systems through the implementation of asymmetric injection in non-axisymmetric-aperture shaped nozzle (trapezoidal, biconvex, triangular) with  
10 a flow path width greater than its height.

Additionally, these nozzles may possess curved or straight flow path walls wherein corners made by any two sidewalls are not perpendicular and contain a swept or non-swept trailing edge. The nozzle on the present  
15 invention has multiple injectors proximate to the throat of the nozzle and/or proximate to the nozzle flap. These injectors are used to vary the throat area (sonic plane) and/or vector angle of the fluid flow. Dedicated sets of these injectors can be arrayed around  
20 the periphery of the nozzle to achieve throttling and vectoring in pitch and/or yaw planes. This is illustrated in FIGURES 1A - 1C.

FIGURE 1A is an isometric depiction of a high aspect ratio biconvex aperture nozzle with injection  
25 ports for multi-axis thrust vectoring. FIGURE 1B presents a plan view of high aspect ratio aperture nozzle 10 illustrating injector ports 12 and 14. Throat slots 12 serve as injector ports proximate to the throat of the nozzle and flap slots 14 serve as  
30 injector ports proximate to the nozzle flap. FIGURE 1C

illustrates two additional sets of injectors yaw slots  
16 and pitch slots 18. These dedicated sets of  
injectors 12, 14, 16 and 18 can be arrayed around the  
periphery of nozzle 10 to achieve vectoring in pitch  
5 and/or yaw vector planes as is shown in FIGURE 1A by  
thrust vector 19. The injector slots or pitch slots 18  
shown in FIGURE 1C are located on the top and bottom  
surfaces of nozzle 10 and are intended to provide pitch  
plane vectoring. While those injectors such as yaw  
10 slots 16 located on the sidewalls are intended for yaw  
plane vectoring. Slots 12, 14, 16 and 18 can be swept  
at an angle similar to that of the exit plane trailing  
edge. Such injectors direct injected flow having  
vector components,  $I_x$ ,  $I_y$ , and  $I_z$ , opposed to that of  
15 the primary flow vector  $V_{pf}$  in the intended vectoring  
plane,  $yz$  for pitch or  $xz$  for yaw of FIGURE 1D with the  
special cases of a zero sum  $x$  component for pitch or  
zero sum  $y$  component for yaw.

FIGURE 1D illustrates two instances where the  
20 primary flow vector  $V_{pf}$  is shifted in the pitch ( $yz$ ) or  
yaw ( $xz$ ) plane. In both instances,  $V_{pf}$  which lays  
along the primary flow ( $z$ ) axis, swings to an intended  
vector  $V_i$  by injecting flow to oppose  $V_{pf}$  having vector  
components  $I_{x1}$ ,  $I_{y1}$  and  $I_{z1}$ . In the instance of pitch,  
25  $I_{x1}$  is zero while instance of yaw,  $I_{y1}$  is zero.  
Additional injectors are represented by an injected  
flow having vector components  $I_{xn}$ ,  $I_{yn}$  and  $I_{zn}$ . When  
additional injectors are present, a pure rotation of  
the  $V_{pf}$  in the pitch ( $yz$ ) plane requires that the net  
30 effect of  $\sum_1^n I_{xn}$  on  $V_{pf}$  is zero.



To direct the injector flow at such angles a multi-hole array of injectors, as is shown in FIGURE 2B, having a central axis aligned to provide the aforementioned angles can be used in place of injector slots.

FIGURE 2A presents an ultra high aspect ratio (10:1) trapezoid aperture nozzle with injection ports for yaw thrust vectoring. FIGURE 2B illustrates an array 22 comprising several individual injector ports 24. The throat plane can be varied and inclined to vector fluid flow using only the set of injectors proximate to the throat, the set of injectors proximate to the flap, or using a combination of both sets of injectors.

FIGURE 3A presents a more detailed depiction of an ultra high aspect ratio trapezoid aperture nozzle 30 having injector ports 32 for yaw thrust vectoring. FIGURE 3A presents an isometric view of nozzle 30 with exiting primary flow 34 wherein exiting primary flow 34 is vectored at a 10 degree yaw vector angle 36. FIGURE 3B illustrates an array of slot flap injectors 38 in a trapezoidal aperture nozzle. An alternative embodiment is presented in FIGURE 3C wherein the flap injectors 40 are incorporated into a hexagonal aperture nozzle. Yet another type of slot injector is presented in FIGURE 3D having an array of slot injectors 42 incorporated into a rectangular aperture nozzle. Yet another embodiment of flap injectors is presented in FIGURE 3E where an array of round jet flap injectors 43 are incorporated into a trapezoidal aperture nozzle. These different

shapes can be chosen in order to minimize observable characteristics such as radar return.

FIGURE 4A presents a plan view of nozzle 30 having two fluidic injection ports 44 per side. The nozzle in this case has a 30° trailing edge sweep 46. A rear view of nozzle 30 is provided in FIGURE 4B.

FIGURES 5A-5E provide an additional depiction of an embodiment of the present invention. FIGURES 5A-5E depict various aspects of a high aspect ratio biconvex aperture nozzle 50 with injection ports for multi-axis thrust vectoring. FIGURE 5A presents a rear view (xy plane) of biconvex aperture nozzle 50. Injector slots 52 are used to control the pitch angle of nozzle jet 50 while injector slots 54 are used to control the yaw angle of nozzle 50. FIGURE 5B presents a top down (xz plane) or plan view of the biconvex aperture nozzle 50. FIGURE 5C presents a side view (yz plane) of this biconvex aperture nozzle 50. The yaw and pitch injector slots 52 and 54 are further broken down into throat slots and flap slots as illustrated in the plan view provided in FIGURE 5D. Vectors 55 and 53, where vectors 53 are associated with pitch injector slots and vectors 55 are associated with yaw injector slots, illustrate that control of the primary fluid flow 56 is best achieved when the injector slots direct the injected flow in opposition to the primary flow in the intended vectoring plane as illustrated in FIGURES 5A-5C. FIGURES 5D and 5E again present the throat slots and flap slots associated with the biconvex aperture

nozzle 50 and provide a plan view in FIGURE 5D and a rear view in FIGURE 5E.

CFD solutions can be used to understand the effects of the high aspect ratio aperture shape on the fluidic throat skewing process. For example, with the high aspect ratio nozzle 10 provided in FIGURES 1A - 1C CFD solutions predict a 13 to 14 degree yaw vector angle potential for this configuration at design conditions. FIGURE 6 illustrates the performance envelope for fluidic throat skewing for the selected configuration of design conditions. This graph indicates the performance envelope of yaw vector angle versus effective throat area.

Using computational fluid dynamics (CFD) and design of experiments (DOE) software, the cost and time required to develop a fluidic nozzle is greatly reduced. The advantage of the fluidic nozzle is dramatically reduced weight and cost in high-performance military aircraft.

Fluidic nozzle performance depends on parameters such as injector location, shape, size, and flow rate; nozzle flap length; and injector flow pressure. To investigate eight parameters with three levels each would require  $3^8$  or 6,561 experiments, to handle all the possible combinations.

Design of experiments uses regression analysis to identify statistically significant subsets of the full factorial. There is some sacrifice in accuracy, but the results usually trend in the right direction.

A major advantage of DOE is that it allows all the parameters to vary simultaneously. A single permutation, on the other hand, varies one parameter at a time and cannot deal with interactions among the fixed parameters.

DOE starts with a prescreening exercise and a baseline configuration. The baseline will not meet all the design criteria. If it did, the analysis wouldn't be necessary in the first place.

A figure of merit is established for comparing results. For fluidic nozzle throttling, the figure of merit is the nozzle discharge coefficient, which directly correlates to effective throat area. For thrust vectoring, the figure of merit is primarily jet thrust vector angle and gross thrust coefficient.

The prescreening exercise is much like a typical analysis. Design parameters are varied one at a time to determine which have the greatest effect on the figure of merit. CFD may be used for the screening.

A CAD model of each nozzle/injector shape is constructed. The models may be initially evaluated using two-dimensional CFD analysis. If the results are favorable, then the more time-consuming three-dimensional CFD calculation is performed.

Based on CFD results, the design parameters are reduced to the three or four that produced the greatest response, and multiple levels are assigned to each parameter.

Even with only four variables and three levels for each one, a full permutation is  $3^4$ , or 81 experiments.

5 The subset combinations are processed first  
through 2-D CFD to eliminate unlikely candidates and  
then further analyzed with 3-D. These results are  
post-processed with DOE to develop design  
sensitivities. For instance, a parameter could be  
longer or shorter, higher or lower, to improve  
response. Knowing this information, the researcher can  
develop an optional model, the parameter combination  
expected to deliver the best performance. This model  
10 is then verified by CFD to ensure that DOE has indeed,  
produced an optimal combination. If this combination  
passes the analytical test, the design is ready for  
wind tunnel testing.

15 For nozzle discharge coefficient and thrust  
efficiency, the CFD results are typically within 1 and  
2 percent of the physical experiments' results, while  
vectoring effectiveness has been within 1 and 2  
degrees.

20 One embodiment of the present invention uses CFD  
analysis relying on Reynolds-averaged Navier-Stokes  
code that can use an approximate lower-upper implicit  
solver.

25 This allows boundary conditions inside the grid,  
an important feature when looking at an injector port  
that sits inside the grid. The CFD analysis may also  
allow the problem to be cut into multiple parts so that  
the pieces can be run in parallel on multiple computer  
processors.

30 Calculating these complex CFD problems, some with  
almost two million grid points, demands substantial

computing power. For one million grid points or fewer, a computer such as the Silicon Graphics Octane, a high-performance Unix-based graphics workstation with multiple RISC processors and one gigabyte of RAM or other system known to those skilled in the art, is required for CFD analysis. For larger problems, a super computer such as an HP V-class can be used.

Design of experiments slashes the number of analytical experiments, and computational fluid dynamics eliminates innumerable wind tunnel tests. A typical wind tunnel test alone costs \$250,000 to \$500,000. Military aircraft often have a 10- to 15-year development cycles. The techniques of the present invention cut millions of dollars from development costs, a fact that has made the development work economically feasible.

FIGURE 7 illustrates the design process for fluidic throat skewing using both computational fluid dynamics (CFD) and a design of experiments (DOE) approach. In step 102 the baseline configuration is analyzed of nozzle 104. The design variables are identified such as  $R_1$ ,  $H$ ,  $L_F$ ,  $X_{IFLAP}$ ,  $\alpha_{IFLAP}$ , and the nozzle throat height. Some of the design variables to be selected may include the divergent flap length, the flap injector location, flap injector angle, expansion area ratio, injector mass flow split, total injector mass flow, injector slot distribution, nozzle pressure ratio, convergence rate, aperture shape, aperture aspect ratio, trailing edge angle and trailing edge type. A design study matrix comprising the different design variables and settings is used to

reduce the number of configurations to be studied in step 106.

5        CFD analysis on the different DOE configurations identified in step 106 are performed to determine different design sensitivities such as those described in step 108.

      The detected design sensitivities, illustrated at step 110, in one embodiment indicate a relationship between yaw vector angle and the ratio of  $L_F/H_B$ .

10        An enhanced configuration is constructed in step 112 with the appropriate values of design variables selected from the prior experiments.

15        In step 112, this configuration is evaluated with a static thrust stand test. One embodiment of the present invention selected according to the design process illustrated in FIGURE 7 is contained in table 1.

<u>Design Variable</u>	<u>'Optimum'</u>
Divergent Flap Length	$12 * h_{thr}$
Flap Injector Location	$0.8 * L_f$
Flap injector Angle	$30^\circ$ opposed
Expansion Area Ratio	1.3
Injector Mass Flow Split	Variable for throttling and vectoring
Total Injector Mass Flow	5%
Injector Slot Distribution	Dedicated
Nozzle Pressure Ratio	$2 < NPR < 9$
Aperture Shape	Biconvex
Aperture Aspect Ratio	$(a/b) = 2.5$
Trailing-Edge Angle	$30^\circ$
Trailing-Edge Type	Arrowhead

Referring now to FIGURE 8, an experimental apparatus for determining the effectiveness of pulsed injection is depicted. A flow container 210 having a rectangular shape defines a flow field 212 which contains a fluidic flow 214. Fluidic flow 214 passes over a nozzle contour 216 and leaves flow container 210 at container exit 218. Nozzle contour 216 cooperates with flow container 210 to form a nozzle 220. The cross sectional area of the opening of nozzle 220 varies along the longitudinal flow axis according to the area of the plane between the surface of nozzle contour 216 and the top wall of flow container 210 that is perpendicular to the longitudinal axis and the general vector of fluidic flow 214. Nozzle 220 constricts fluidic flow 214 with nozzle contour 216 in only one dimension to provide an accurate means for testing the effects of a fluidic flow. In other embodiments, nozzle 220 can include any convergent nozzle, divergent nozzle, or combination of convergent and divergent nozzles which accelerate or direct a fluidic flow by constricting the flow. Nozzle 220 has a throat 222 defined as the point along nozzle 220 of greatest constriction, the nozzle opening having the smallest cross sectional area at the throat.

A fluidic flow is provided to the opening through nozzle 220 by an injector 224 that is incorporated with nozzle contour 216 proximate to throat 222. Injector 224 receives pressurized fluid from a duct 226, and provides the pressurized fluid into a flow field 212 through a port formed at the end of injector 224.



FIGURE 8 depicts two separate controllers for pulsing the fluid from injector 224 into nozzle 220 at throat 222. A high speed mechanical valve 228 provides periodic modulation of the pressure to injector 224 by rotating a ring 230 with valve openings 232 so that ring 230 periodically blocks flow through duct 226 and periodically allows flow through duct 226 when valve opening 232 corresponds to duct 226. The mechanical valve can provide a square pulse wave form having an amplitude that shifts from zero secondary flow to full secondary flow in a short transition time. FIGURE 8 also depicts an acoustic pulse vibrator 234 associated with injector 224. Acoustic pulse vibrator 234 can be any vibrational device that provides modulated energy to duct 226. For instance, a piezoelectric vibrator can provide acoustic energy, similar to the energy produced by a stereo sound system. An acoustic vibrator can produce a wide variety of wave forms. In other embodiments, any effective means of modulating a flow can be used.

Injector 224 provides a pulsed fluidic flow field 212, with the pulse determined by a controller, such as mechanical valve 228 or acoustic pulse vibrator 234. The controller associated with injector 224 can vary the pulse of the fluidic flow to have a predetermined frequency, amplitude, or wave form. For instance, mechanical valve 228 can vary the frequency of the pulse provided by injector 224 by varying the rate at which ring 230 rotates. In this example, the pulsed fluidic flow produced by injector 224 modulates from no

flow when valve openings 232 are completely misaligned with duct 226 to having a full flow equal to the flow through duct 226 when valve openings 232 are completely aligned with duct 226. Mechanical valve 228 can  
5 provide a pulsed fluidic flow with varying amplitudes by either varying the pressure available in duct 226 or making valve opening 232 smaller relative to the size of duct 226, thereby reducing the flow to injector 224. Acoustic pulse vibrator 234 can provide a pulsed  
10 fluidic flow having a predetermined wave form by creating vibrations with a corresponding wave form along duct 26. For instance, a sinusoidal electrical signal provided to a piezoelectric vibrator could create sinusoidal mechanical energy along duct 226  
15 which can be transmitted to the secondary flow through duct 226.

In operation, a primary fluidic flow 214 passes through flow container 210 towards container exit 218 along flow field 212. The fluidic flow can be any  
20 fluid, such as liquids or gases. As fluidic flow 214 passes through throat 222 of nozzle 220, injector 224 injects an unsteady or pulsed fluidic secondary flow across flow field 212. Although FIGURE 8 depicts a flow that is generally perpendicular to flow field 212,  
25 the flow could be injected at any angle opposed to or with the direction of fluidic flow 214. A pulsed laser 236 provides a laser beam to a mirror 238 which reflects the beam through a lens 240. The refraction of the beam as it passes from lens 240 through the flow  
30 214 allows a visual determination of the effects of the

pulsed fluidic flow upon flow 214. Blockage can be determined by measuring the primary fluid mass flow 214 upstream of the test section with a calibrated meter.

5 Blockage of a primary flow through a nozzle by a secondary flow is related to the extent of penetration of the secondary flow into the primary flow. The penetration of a secondary flow into a primary flow is controlled by the secondary/primary flow momentum flux ratio, which is related to the mass and velocity of the  
10 primary and secondary flows, and the change in velocity of the flow as it pulses. The greater the mass and velocity of a secondary flow exiting an injector relative to the mass and velocity of a primary flow passing by the injector, the greater the penetration of  
15 the flow into the fluidic flow. Increased penetration of the secondary flow can provide greater blockage of the primary flow through the nozzle, effectively decreasing the cross sectional area of the nozzle opening at the point of penetration.

20 Penetration of a secondary flow into a primary flow can be enhanced when the flow rate is periodically modulated, or pulsed. Pulsing of an injector's flow rate forms trains of vortex rings with spacing and strength related to the characteristics of the pulse,  
25 such as the pulse's frequency, amplitude and wave form. The vortex rings created by the pulsed flow interact with the primary flow to enhance penetration of the flow into the primary flow by increasing the flow's net field momentum flux ratio. When placed proximate to  
30 the opening of a nozzle, such as at a nozzle's throat,

an injector can increase the blockage of a flow through a nozzle by penetrating the flow, and effectively decreasing the cross sectional area of the opening of the nozzle. The amount of blockage will vary with the magnitude, characteristics, and available frequency of vortex ring production. For instance, low frequency mechanical valves can induce strong perturbations with vortex-ring-induced penetration due to the large shifts in amplitude available from such valves; in contrast, acoustic vibrations can introduce higher frequency pulse wave forms with smaller perturbations but less disruption to secondary flow pressure. Alternatively, a combination of mechanical and acoustic induced vibrations can produce unique primary flow disruption characteristics. Due to the interaction of the vortex rings with the primary flow 214, maximum blockage of nozzle 220 for a given primary flow 214 could occur at frequencies that are different than the frequency that provides greatest penetration into flow 214.

The apparatus depicted in FIGURE 8 allows an experimental determination of maximum blockage for a particular nozzle contour with a primary flow and a variety of secondary flows. First, a baseline for the blockage caused by steady-state injection can be determined for a particular primary to secondary flow velocity ratio. An unsteady flow or pulsed flow, meaning a flow modulated over time, can then be injected into the primary flow, with the unsteady or pulsed flow having the same mean flow rate as the steady flow. At proper frequencies, amplitudes and

waveforms, pulsed injection of the secondary flow provides enhanced blockage over the blockage provided by steady state injection due to the vortex rings formed as the flow changes over time. The pulsed flow  
5 can be tuned by testing different pulsing frequencies, amplitudes and waveforms to achieve maximum blockage for a given mean flow rate of the secondary flow. Thus, a pulsed flow injector can increase fluidic blockage of a primary flow through a nozzle compared to  
10 the blockage provided by a steady-state injector because of the periodic modulation of the injectant, the increased blockage being created without a net increase in time-averaged injectant mass flow.

It is important to understand that, as used  
15 herein, a pulsed flow is a flow with mass flow characteristics that change periodically over time in a regular or repeated pattern. A pulsed secondary flow can achieve a predetermined blockage of a given primary flow to support flow throttling or vectoring. The  
20 periodic changes can be a pulse having a particular frequency, wave form or amplitude that maximizes blockage by maximizing the momentum flux for a given mean flow rate.

In alternative embodiments, an unsteady flow can  
25 be used to achieve a predetermined blockage of a given primary flow. As used herein, an unsteady flow means a flow with mass flow characteristics that change over time but that do not necessarily change in a particular or periodic repeated pattern. A pulsed flow is a type  
30 of unsteady flow. An unsteady flow can maintain

constant blockage of a nozzle opening for a given  
primary flow because of the vortices created by the  
change in the mass flow characteristics of the flow  
even though the change in mass flow characteristics  
5 does not follow a repeating pattern. As used herein,  
an unsteady flow does not mean changes in mass flow  
characteristics of a flow if the changes are to  
increase or decrease nozzle blockage for a constant  
primary flow, or if the changes are to maintain a  
10 constant nozzle blockage in response to changes in the  
mass flow characteristics of the primary flow, as could  
occur with changing throttle settings for a jet engine  
having steady secondary flow injection.

FIGURE 9 depicts a jet engine configured with a  
15 pulsed fluidic secondary flow injector according to the  
present invention. A primary flow 214 of air enters  
jet engine 242 through intake 244. Fan section 246,  
comprised of a plurality of rotating fan blades 248,  
pushes flow 214 into bypass section 250 and compressor  
20 section 252. Compressor section 252 is comprised of a  
plurality of compressor blades 254 which compress flow  
214 into combustion chamber 256. Fuel is mixed with  
flow 214 in combustion chamber 256 and ignited, thereby  
adding energy to flow 214, resulting in an increased  
25 temperature of flow 214 in combustion chamber 256.  
Pressure within combustion chamber 256 forces flow 214  
into turbine section 258, which is comprised of a  
plurality of turbine blades 260. Turbine section 258  
removes some energy from flow 214 to power compressor  
30 section 252 and fan section 246. Flow 214 then passes

into exhaust chamber 262 where it combines with the  
flow from bypass section 250. An afterburner 264 can  
provide additional fuel which can be ignited to  
increase the energy of flow 214. Flow 214 is then  
5 expelled from engine 242 through exit 66 as an exhaust  
flow.

Engine 242 creates thrust related to the velocity  
of the mass and density of the air of flow 214 over a  
given time period. Typically, in a jet engine, flow  
10 214 is a subsonic flow of air until it reaches throat  
270. A nozzle 268 cooperates with exit 266 to accept  
flow 214 from exhaust chamber 262 and to accelerate  
exhaust flow 214 to higher velocities, typically  
supersonic velocities. To achieve optimum acceleration  
15 of the exhaust flow, nozzle 268 converges the flow at  
throat 270, which is the point or section in nozzle 268  
having the smallest cross sectional area, the  
constriction of throat 270 typically accelerating the  
flow to a sonic velocity, and a supersonic velocity  
20 after throat 270. Constriction of the flow at throat  
270 operationally translates energy in the flow from  
pressure and temperature into velocity, thus creating  
thrust opposite to the vector of flow 214 as flow 214  
exits nozzle 268. Although nozzle 268 is depicted as a  
25 fixed geometry nozzle, it should be understood that  
variable geometry nozzles can be incorporated with the  
present invention to enhance control of the exhaust  
flow.

An air duct 274 collects high pressure air from  
30 flow 214 at compressor section 252 and provides the

high pressure air to injector 276. In alternative  
embodiments, air duct 274 can collect air from bypass  
section 250 combustion chamber 256 or any other portion  
of engine 242 having high pressure air. In an  
5 alternative embodiment, a separate compressor can  
provide high pressure air to air duct 274. A  
controller 278 controls the pressurized air in duct 274  
to create an unsteady or pulsed secondary flow and to  
send that secondary flow to injector 276 for injection  
10 proximate to nozzle 268. Proximate to nozzle 268, as  
used herein, means a position that will result in some  
blockage of nozzle opening 272 by the interaction of  
the secondary flow from injector 276 and exhaust flow  
14 exiting exhaust chamber 262. Air duct 274 can  
15 provide compressed air to two or more opposing  
injectors 276 located on opposite sides of the interior  
wall of nozzle 268.

In operation, controller 278 can vary the  
frequency, amplitude, and wave form of the pulsed  
20 secondary flow from injector 276 so as to optimize  
performance of engine 242. For instance, to enhance  
the acceleration of exhaust flow 214 as it exits from  
exhaust chamber 262 through exit 266, the effective  
cross sectional area of nozzle opening 272 can be made  
25 smaller. Controller 278 can direct each of opposing  
injectors 276 to inject a pulsed secondary flow having  
mass flow and pulse characteristics adequate to  
effectively decrease the cross sectional area of  
opening 272 of nozzle 268 to not only ensure proper  
30 acceleration of exhaust flow 214, but also to throttle



flow 214 to control the pressure and temperature within exhaust chamber 262. If each injector 276 injects a secondary flow with similar characteristics, flow 214 can be accelerated without changing its vector. In one  
5 embodiment, a mechanical valve could provide a square pulse waveform with a frequency of between 100 and 1000 hertz. In another embodiment, each injector 276 could be controlled by its own associated controller 278. Controller 278 can include a processor and software to  
10 control a nozzle's effective cross sectional area over a range of operating conditions.

When engine 242 is operated at varying power settings, the energy level of flow 14 is varied by, for instance, fluctuation of the amount of fuel in  
15 combustion chamber 256. A greater energy level added to flow 214 increases the pressure and temperature in exhaust chamber 262. Typically, jet engines increase the cross sectional area of the nozzle when afterburner is selected. At high flow energy levels, controller  
20 278 can direct injector 276 to provide a secondary flow with decreased blockage to reduce pressure in exhaust chamber 262 by creating a greater effective cross sectional area in opening 272. When the energy level of flow 214 is maximized by providing fuel into exhaust  
25 chamber 262 with afterburner 264 the exhaust flow in exhaust chamber 262 can create an over-pressure which can cause a backflow of air through bypass chamber 250 and, in extreme situations, through turbine section 258. To minimize the effects of the backpressure  
30 created in exhaust chamber 262 by initiation of

afterburner 264, controller 278 can direct injector 276 to provide no or just minimal blockage of nozzle opening 272, thus effectively increasing the cross sectional area of nozzle opening 272. Those skilled in the art will appreciate that the system depicted in FIGURE 9 can perform or supplement the functions of a variable geometry nozzle to adjust the effective cross sectional area of a nozzle over a jet engine's full power range.

FIGURE 10 depicts one embodiment of injectors 276 and 277 according to the present invention, and the effect that injectors 276 and 277 can have on flow 214 exiting an exhaust chamber 262 through nozzle opening 272. When injectors 276 and 277 are turned off so that they do not inject a secondary flow, the effective cross sectional area of nozzle opening 272 is defined by the area of the plane generally perpendicular to flow 214 between the walls 280 of nozzle 268. When symmetric and opposed injectors 276 and 277 are provided similar secondary flows 284 and 285 into flow 14, the secondary flows evenly block the nozzle's opening to vary the nozzle's discharge coefficient, which is analogous to effective cross sectional flow area, to decrease the effective cross sectional area of nozzle opening 272 to the area depicted by numeral 282. Thus, nozzle opening 272 depicts an effective cross sectional area that could correlate to an engine in afterburner, and nozzle opening 282 depicts an effective cross sectional area that could correlate to an engine when not afterburning.

Modern jet aircraft typically use variable geometry nozzles to control throat area. In an afterburning turbofan engine, as much as a two-fold increase in throat area can be required to throttle engine operating pressure and control stall margin during afterburner operation. To achieve a minimum possible effective throat area, injector 276 and 277 can include several features in addition to pulsed flow.

First, injector 276 and 277 may provide an airflow with maximum penetration into the primary flow 214. To achieve the best penetration, injector 276 should provide a sonic or supersonic secondary flow 284, such as can be obtained from a choked injector having an expansion area ratio of approximately 1.1. The supersonic velocity of the injected secondary flow should also provide optimal mass flow characteristics. Injectors 276 and 277 should provide a secondary flow with a corrected mass flow parameter and secondary to primary total pressure ratio that are as large as possible to enhance reduction of the nozzle's discharge coefficient. For example, an injected corrected mass flow of 15%, and a total pressure ratio of 2, relative to the primary flow, are estimates of the maximum allowable properties within aircraft system weight and volume design constraints. In one alternative embodiment, the mass flow characteristics could be further enhanced by the addition of ignited fuel or other injectants to the secondary flow.

Next, the orientation and location of injectors 276 and 277 can be arranged to maximize penetration into primary flow 214. Injectors 276 and 277 provide secondary flow 284 that is at an injection angle 286 from being completely opposed to the direction of primary flow 214 along the longitudinal axis of nozzle 268. FIGURE 10 depicts angle of 286 as 15 degrees from the longitudinal axis of nozzle 268, although angles of between zero and 30 degrees will provide enhanced blockage of nozzle opening 272. In one alternative embodiment, the angle 286 of injectors 276 and 277 can be adjusted to a range of values. Injector 276 is located at the beginning of throat 270 so that the secondary flow from injector 276 is aimed into the subsonic portion of the nozzle flow field 12. Injection of the secondary flow into the subsonic portion of the flow field prevents the formation of shocks, which can significantly impact the nozzle's thrust efficiency.

Finally, injectors 276 and 277 can be incorporated into various nozzle designs so that the nozzle design, injector mass flow characteristics, injector orientation, injector location and the secondary flow pulse characteristics cooperate to provide maximum blockage for a given secondary flow. Referring to FIGURE 11, one effective internal nozzle convergence contour is depicted. Exhaust chamber 262 is adapted to accept engine exhaust at an afterburner duct 290, and to provide the exhaust to throat 270. Exhaust chamber 62 has a high discharge, smooth transition contour

shape. Although exhaust chamber 262 can have a variety of profiled choked nozzle convergence shapes to enhance the effect of injectors 276, an ellipse shape is depicted in FIGURE 11. The ellipse shape has a major axis 292 with vertices along its major axis having a length depicted as  $a$ , and a minor axis 94 with a vertices along its minor axis having a length depicted as  $b$ . The afterburner duct 290 into exhaust chamber 262 has a diameter proportional to major axis 292, such as four times the distance  $a$ . Length  $b$  of minor axis 294 establishes the contraction ratio of nozzle 268, meaning the ratio of the areas of afterburner duct 290 and throat 270, and can be set at a value similar to that of the F110-GE-129 turbofan engine's nozzle, such as approximately 1.8.

The ellipse shape of exhaust chamber 262 depicted in FIGURE 11 blends into throat 270 with a fillet-radius shaped convergence section 296. Throat 270 has a constant area along a throat length from its intersection with convergence section 296 to its intersection with a divergent section 298, the length being proportional to major axis 292, such as a length of  $a$ . The nozzle's discharge coefficient is raised without injection and lowered with injection. Divergent section 298 accepts flow 214 from throat 270 and directs flow 214 along a length  $c$  of approximately 12 inches to ensure reattachment of flow 214 to the walls of nozzle 268 before flow 214 is discharged through exit 266. Divergent section 298 has a low degree of expansion, such as an expansion area ratio of

1.1-1.3 where expansion area ratio is defined as the cross sectional area at exit 266 divided by the cross sectional area of throat 270. The low degree of expansion of divergent section 298 reduces the nozzle's discharge coefficient with injection.

Throat 270 can have a number of aperture shapes, including an axisymmetric, rectangular (2-D), elliptical, diamond, triangular shapes, and other low observable RADAR and IR configurations. FIGURE 11 depicts a rectangular throat aperture which supports two opposing injectors 276 formed as slots that encompasses the full periphery of the top and bottom of the rectangular-shaped throat 270. Each injector 276 can provide a uniform flow along the entire slot from a single duct, or can include a number of smaller injection components within each slot which can cooperate to provide a uniform flow or a flow that varies along the slot. Injector 276 is placed within throat 270 proximate to exhaust chamber 262, such as one nozzle throat radius from the nozzle's centroid 300.

In operation, exhaust chamber 262 accepts an exhaust flow 214 from a jet engine through afterburner duct 290 and directs flow 214 through throat 270 and divergent section 298 to exit through opening 266. Flow 214 accelerates as it passes through throat 270 to produce thrust opposite the direction of flow 214. The interaction of the high discharge smooth transition contour shape of exhaust chamber 262 with the proportionally-shaped throat allows nozzle 268 to

operate at a relatively low pressure within exhaust chamber 262. The relatively low pressure within exhaust chamber 262 allows flow 214 to enter afterburner duct 290 and throat 270 at subsonic speeds, but to accelerate to supersonic speeds as it passes through throat 270 and expands into divergent section 298. Thus, a secondary flow from an injector 276 located proximate to throat 270 will not cause the creation of a shock wave if the secondary flow is directed at flow 214 when it is subsonic. Flow 214 reaches supersonic speeds along a sonic plane 302 which is depicted in FIGURE 12, and which occurs after flow 14 passes injectors 276 and 308. Sonic plane 302 divides flow 214 into a subsonic portion proximate to exhaust chamber 262 and a supersonic portion proximate to exit 266.

Referring now to FIGURE 12, lines 304 represent the mass flow characteristics of flow 214, passing through nozzle 268. As flow 214 passes through throat 270, the energy of flow 214 is translated from a high pressure and low velocity into a low pressure and high velocity. Injectors 276 and 308 provides a flow that partially blocks throat 270 and thus skews sonic plane 302 of flow 214. When a plurality of injectors provide a symmetrical secondary flow around the periphery of throat 270, the effective cross sectional area of throat 270 is decreased, causing an increase in pressure within exhaust chamber 262 and an increase in the velocity of flow 214 as it accelerates through throat 270. The pressure within afterburner duct 88

can be controlled by controlling the amount of blockage provided by the secondary flow from injectors 76.

When an injectors 276 and 308 provide an asymmetric flow around the periphery of throat 270 into the subsonic flow 214, flow 214 expands more rapidly along the nozzle wall associated with the greater blockage of throat 270, inducing the expanding flow proximate to the greater blockage to reach sonic speeds more rapidly than flow distal to the greater blockage. The ten degree deflection indicated by angle 306 reflects the vectoring of thrust which could result from the introduction of an asymmetric flow at the subsonic portions of flow 214. The asymmetry of the flow can be created by a number of variations to the flow from each injector 276 and 308 including variations to the injection orientation, mass flow characteristics, and pulse frequency, wave form, and amplitude. The asymmetric flow is created because each injector 276 and 308 has defined, localized influence on flow 214, which can be further controlled by separating each injector with sidewalls.

Supplemental injection port 308 enhances thrust vectoring produced by an asymmetric flow from injectors 276 by providing an additional flow to flow 214 aft of sonic plane 302. Port 308 provides an additional flow to skew sonic plane 302 towards port 308, but does not produce a shock wave.

The throttling and vectoring functions of nozzle 268 can be combined to provide a versatile nozzle design for afterburning, low observable or other



engines. Total injected mass flow from injectors 276  
and 308 can control throttling by providing a proper  
amount of blockage of nozzle 268 at throat 270. The  
distribution of the injected mass flow asymmetrically  
5 between different injectors provides vectoring for a  
given throttle setting, with the angle of vector  
dependent upon the distribution of the injected mass  
flow. Similarly, variations in pulsing characteristics  
and injector orientation can provide simultaneous  
10 throttling and vectoring of flow 214 with an effective  
nozzle. In a nozzle having some variable geometry  
characteristics, variations in the contour and shape of  
the exhaust chamber, convergence section, throat and  
divergent section can also enhance vectoring of flow  
15 214.

A nozzle that provides a combination of throttling  
and vectoring of an exhaust flow from a jet engine can  
provide many advantages, particularly in high  
performance tactical aircraft. A fixed nozzle  
20 comprised of thermally-optimized materials, as opposed  
to mechanically-oriented materials, can be incorporated  
into an aircraft, dramatically decreasing the weight  
and complexity of the aircraft's propulsion system.  
The thrust produced by exhaust flow from the aircraft's  
25 engine can produce pitch and yaw vectors without the  
movement of external surfaces, resulting in smaller  
external surfaces at the tail of the aircraft and an  
associated reduction in aircraft drag. A fixed nozzle  
can also be applied to non-circular aperture shapes.  
30 Injection of a secondary flow into the subsonic primary

flow can produce vectoring and throttling without creating shocks and the thrust losses associated with such shocks.

5        Although the present invention has been described in detail, it should be understood that various changes, substitutions and alterations can be made hereto without departing from the spirit and scope of the invention as defined by the appended claims.

WHAT IS CLAIMED IS:

1. A system for vectoring a primary flow by  
varying an effective throat or sonic plane within the  
primary flow, comprising:

5 an opening for accepting the primary flow;

at least one primary injector located wherein said  
at least one injector is inclined to oppose the primary  
flow;

10 at least one supplemental injector wherein said at  
least one supplemental injector is located downstream  
of the at least one primary injector, wherein said at  
least one supplemental injector is inclined to oppose  
the primary flow, and wherein the at least one primary  
and supplemental injectors provide a flow field opposed  
15 to a subsonic portion of the primary flow in order to  
vector the primary flow; and

at least one controller operable to direct said at  
least one primary and supplemental injector to provide  
a flow operable to vary the effective throat.

20

2. The system of Claim 1, wherein said at least  
one controller is operable to vector the primary flow  
along an intended vector.

25 3. The system of Claim 2, wherein said intended  
vector is contained within an intended vector plane.

30 4. The system of Claim 3, wherein said at least  
one primary and supplemental injectors provide a flow  
field opposed to the primary flow in said intended

vectoring plane, parallel to said intended vectoring plane in a longitudinal plane, and that is parallel to the primary flow axis in a third plane orthogonal to said intended vector.

5

5. The system of Claim 1, wherein a location, size, and/or orientation of said effective throat are varied.

10

6. The system of Claim 1, further comprising:  
at least one mechanical actuator coupled to said at least one controller, wherein said at least one controller directs said at least one mechanical actuator to provide at least one fluidic pulse to said at least one primary and supplemental injector.

15

7. The system of Claim 6, wherein said at least one mechanical actuator comprises a mechanical valve.

20

8. The system of Claim 6, wherein the at least one mechanical actuator comprises an acoustic vibrator.

25

9. The system of Claim 6, wherein said at least one primary and supplemental injector rotates relative to said throat of the nozzle.

10. The system of Claim 1, wherein said controller further comprises:

a processor operable to execute software instructions to control the effective throat of the primary flow over a range of operating conditions.

5           11. The system of Claim 1, wherein a fluidic pulse from said at least one supplemental injector is operable to skew a boundary of the sonic plane of the primary flow towards said at least one supplemental injector.

10           12. The system of Claim 1, wherein the primary flow has a temperature and wherein said pulsed secondary flow throttles the primary flow by decreasing the effective cross sectional area of the effective  
15           throat to control said temperature of the primary flow.

            13. The system of Claim 1, wherein the primary flow has a pressure and wherein said flow throttles the primary flow by decreasing the effective cross  
20           sectional area of the effective throat to control said pressure of the primary flow.

            14. The system of Claim 1, wherein the primary flow has a massflow and wherein said flow throttles the  
25           primary flow by decreasing the effective cross sectional area of the throat to control said massflow of the primary flow.

            15. The system of Claim 1, wherein said at least  
30           one primary and supplemental injector provides a

symmetric flow field in order to vector the primary flow.

5           16. The system of Claim 1, wherein said at least one injector provides an asymmetric flow field in order to vector a primary flow exhaust.

10           17. The system of Claim 1, wherein said at least one controller directs said at least one primary and supplemental injector to simultaneously throttle and vector the primary fluidic flow.

15           18. The system of Claim 1, wherein the primary flow is contained within a fixed geometry nozzle.

          19. The system of Claim 1, wherein the primary flow is contained within a variable geometry nozzle.

20           20. The system of Claim 1, wherein the primary flow is contained within a nozzle integral to a jet engine onboard an aircraft.

25           21. The system of Claim 1, wherein said pulsed secondary flow comprises fuel injected by said at least one primary and supplemented injector.

          22. The system of Claim 21, wherein said injected fuel serves as an after burner.

23. The system of Claim 1, wherein said at least one primary and supplemental injector injects a sonic pulsed secondary flow.

5           24. The system of Claim 1, wherein said at least one primary and supplemental injector injects a subsonic pulsed secondary flow.

10           25. The system of Claim 1, wherein said at least one primary and supplemental injector injects a supersonic pulsed secondary flow.

15           26. A method for controlling a primary flow by varying an effective throat, comprising the steps of:  
            directing a primary flow through a structure wherein the primary flow has a subsonic region prior to the effective throat; and  
            directing a pulsed secondary flow opposed to the primary flow to vary an effective size, location, and  
20           orientation of the effective throat, wherein said pulsed secondary flow is injected to oppose the primary flow from at least one primary injector and at least one supplemental injector location downstream of said at least one primary injector.

25           27. The method of Claim 26, wherein said structure is a nozzle.

30           28. The method of Claim 27, wherein said nozzle is selected from the group of nozzles consisting of

high aspect ratio biconvex aperture nozzle and ultra  
high aspect ratio trapezoid aperture nozzle.

29. The method of Claim 28, wherein said at least  
5 one primary injector and at least one supplemental  
injector are slot type injectors, wherein said at least  
one primary and supplemental injectors provide a  
secondary flow field opposed to the primary flow in an  
intended vectoring plane, parallel to said intended  
10 vectoring plane in a longitudinal plane, and parallel  
to an axis of the primary flow axis in a third plane  
orthogonal to an intended vector of the primary flow.

30. The method of Claim 28, wherein said at least  
15 one primary injector and at least one supplemental  
injector are arrays of injectors, wherein said at least  
one primary and supplemental injectors provide a  
secondary flow field opposed to the primary flow in an  
intended vectoring plane, parallel to said intended  
20 vectoring plane in a longitudinal plane, and parallel  
to an axis of the primary flow axis in a third plane  
orthogonal to an intended vector of the primary flow.



METHOD AND APPARATUS OF ASYMMETRIC INJECTION  
INTO SUBSONIC FLOW OF A HIGH ASPECT  
RATIO/COMPLEX GEOMETRY NOZZLE

ABSTRACT OF THE INVENTION.

The present invention reveals a method and apparatus for controlling the effective area and thrust vector angle of a fluid flow. In one embodiment, the fluid flow is controlled in an advanced, high aspect ratio, complex aperture geometry nozzle using asymmetric injection into the subsonic portion of the fluid flow. The present invention vectors the primary flow by partially blocking the flow with an opposed flow across the flow field. A fluidic flow field is defined in a flow container that directs a pressurized, primary fluidic flow from the container towards an exit of the container. A nozzle may cooperate with the exit of the flow container to control the fluidic flow as it exits the flow container. One or more injectors associated with the container are proximate to the effect throat of the primary flow while other are located downstream of to introduce an opposing fluidic flow that interacts with the primary fluidic flow. A controller associated with the injectors directs the injectors to provide the opposing flow as needed to achieve a desired partial blockage of the primary flow, thereby vectoring the primary flow.

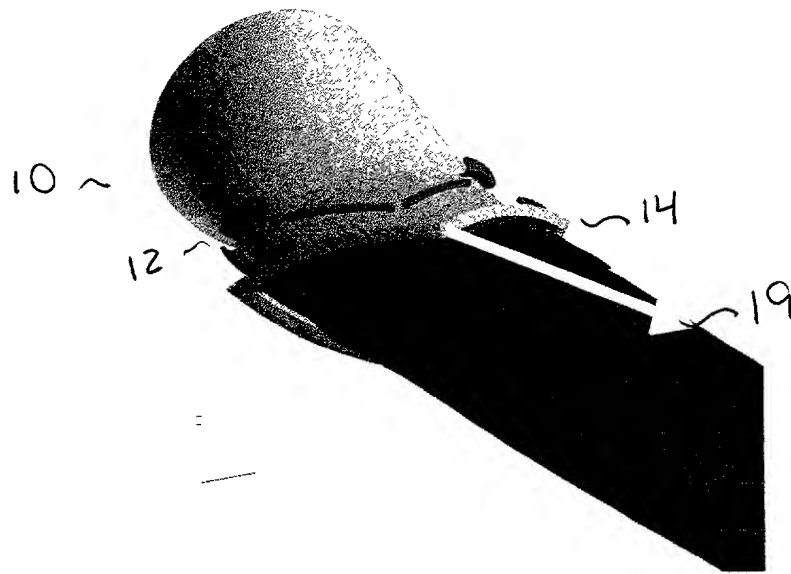


FIGURE 1A

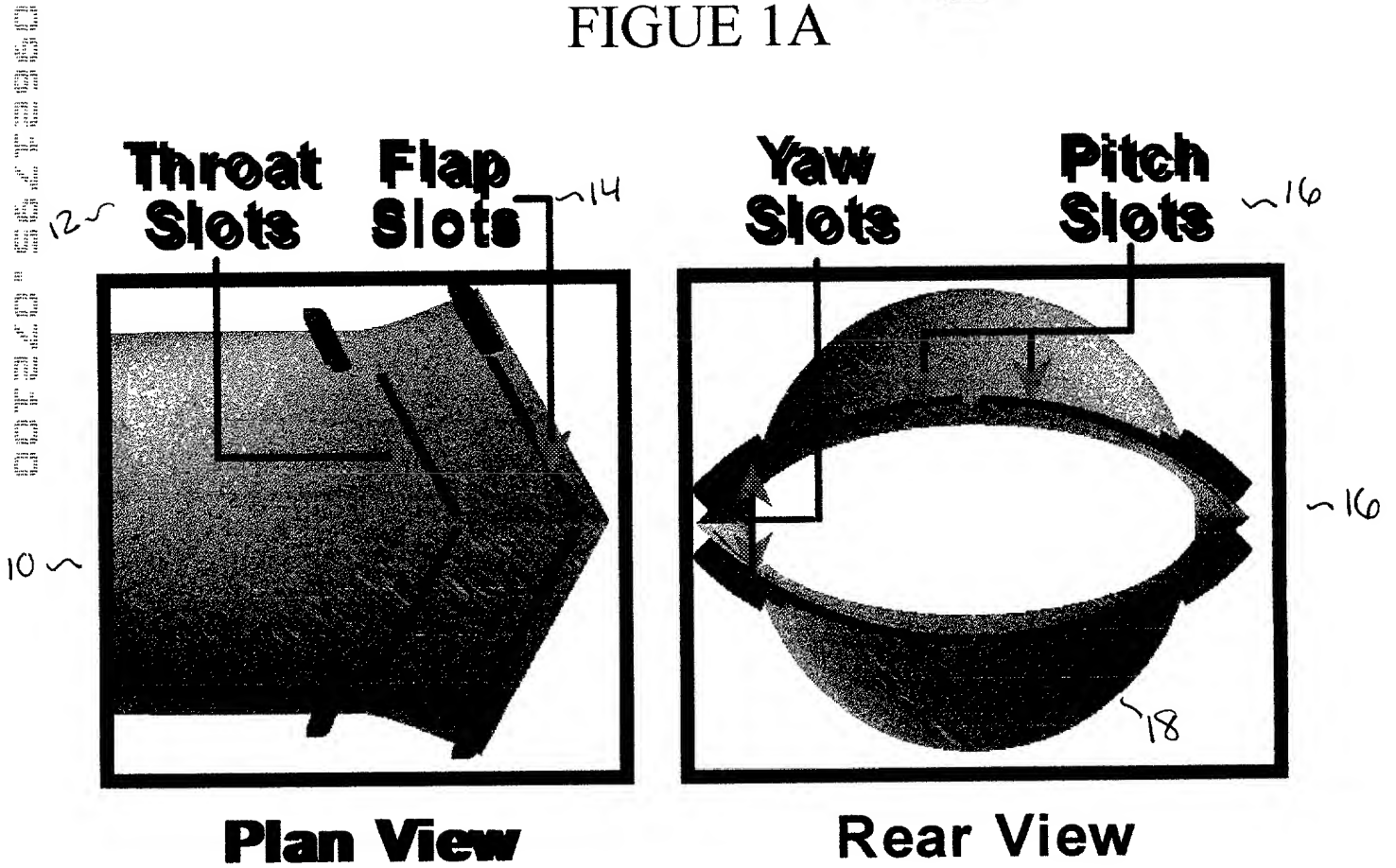
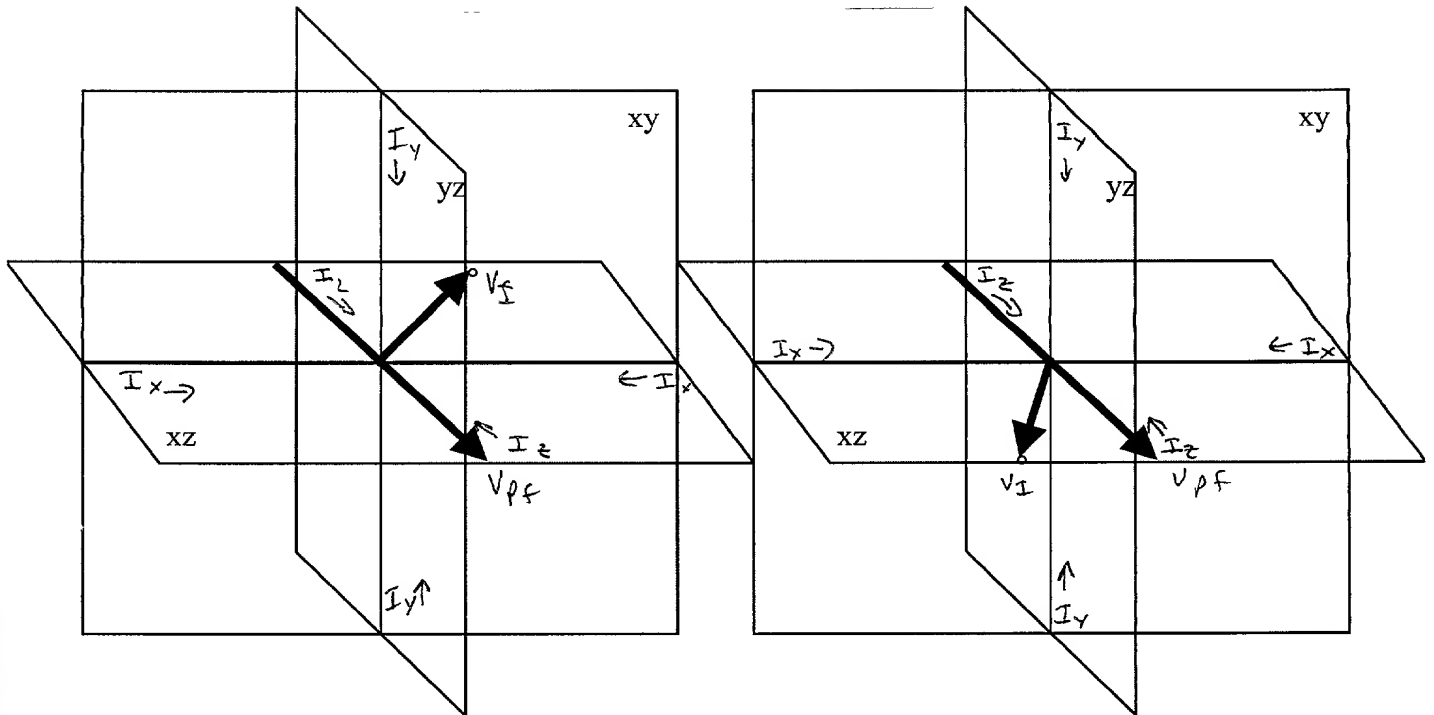


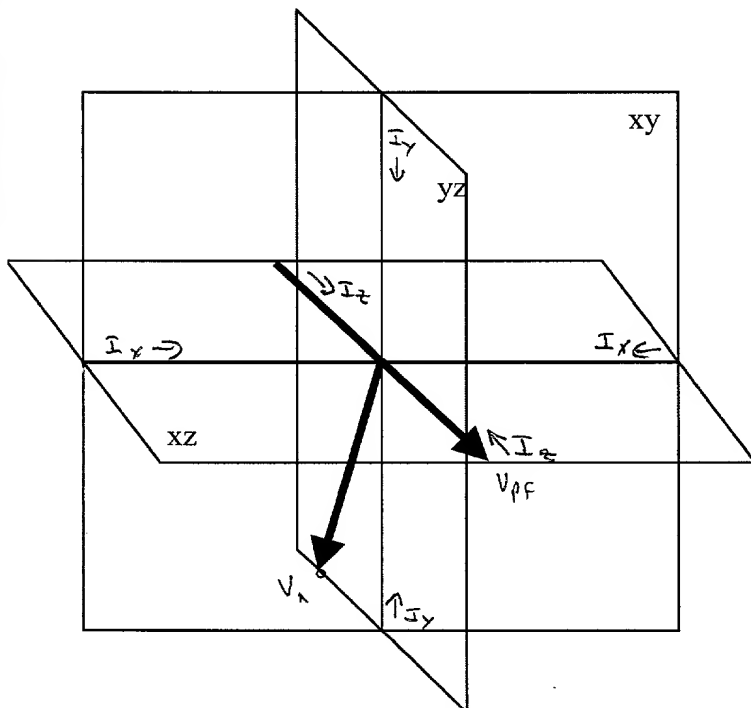
FIGURE 1B

FIGURE 1C



Pitch only  
netsum of  $I_x$  on  $V_{pf}=0$

Yaw only  
netsum of  $I_y$  on  $V_{pf}=0$



Combination of Pitch and Yaw

**FIGURE 1D**

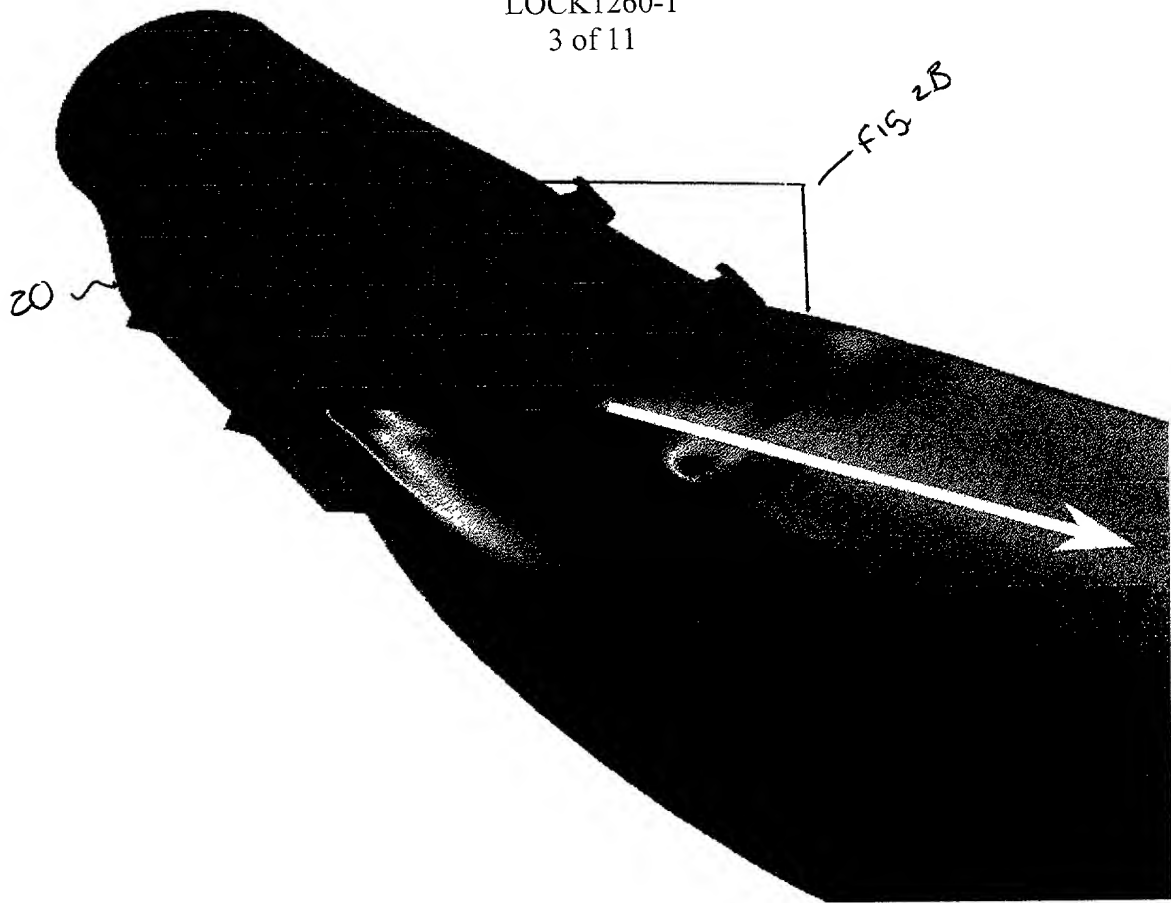


FIGURE 2A

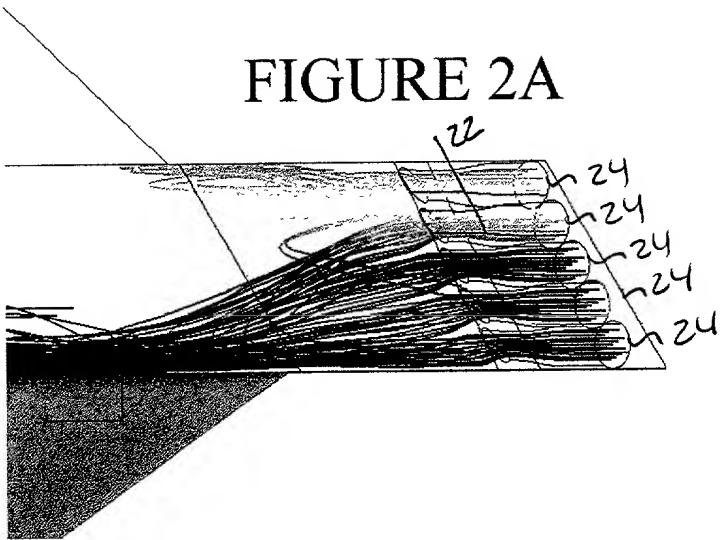


FIGURE 2B

FIGURE 3B

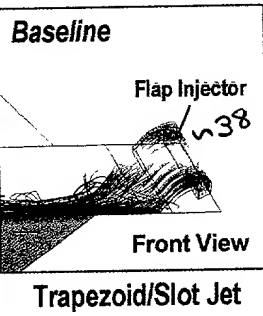
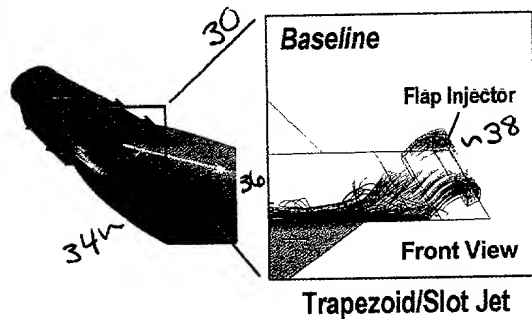


FIGURE 3D

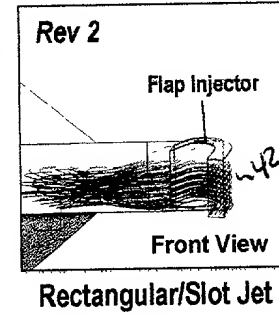
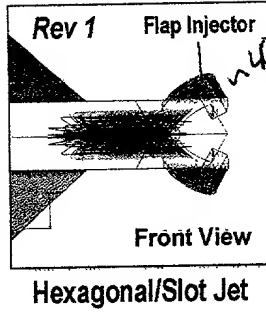


FIGURE 3C

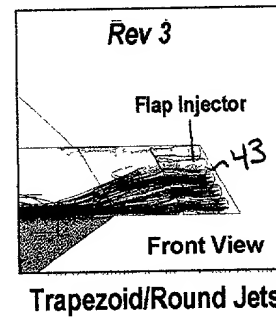


FIGURE 3E

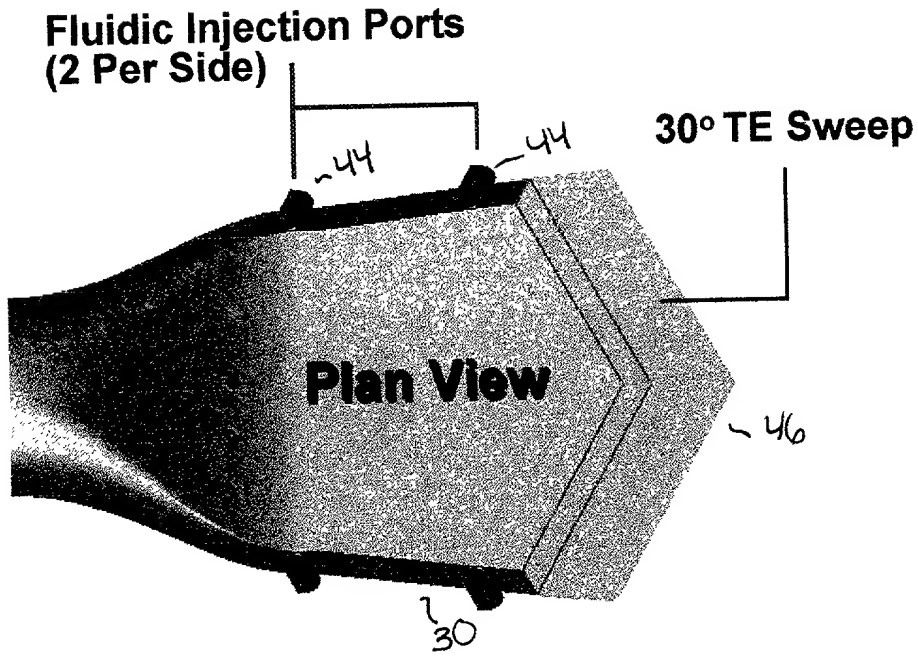


FIGURE 4A

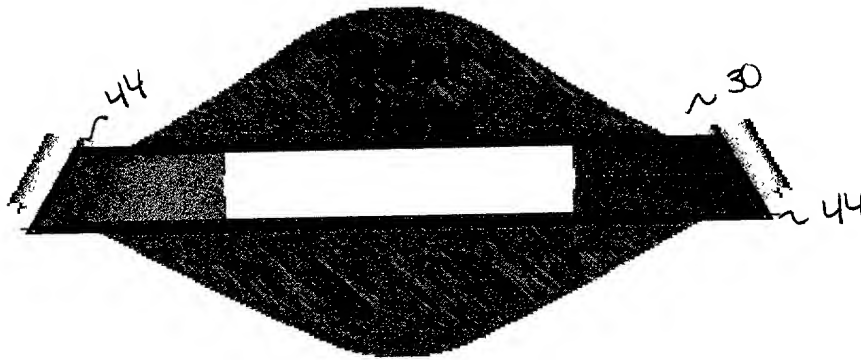


FIGURE 4B

→ Pitch Injection  
→ Yaw Injection

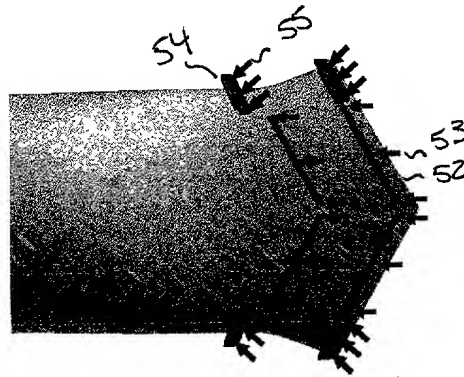


FIGURE 5B

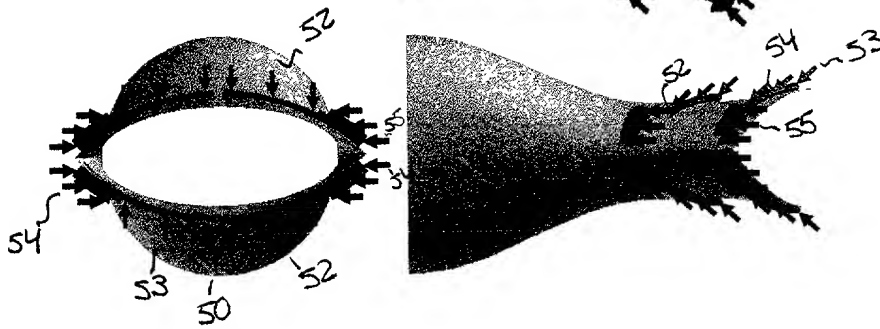
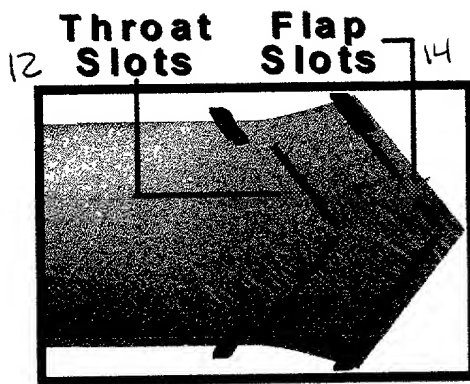


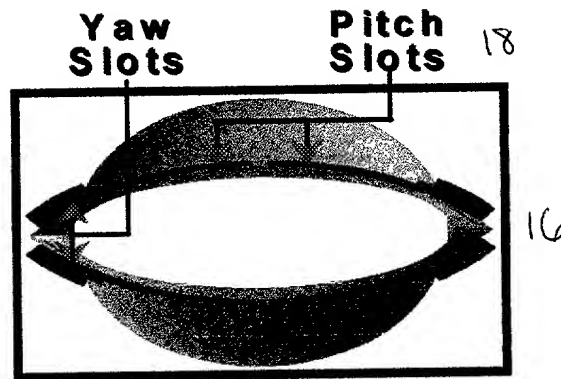
FIGURE 5C

FIGURE 5A



Plan View

FIGURE 5D



Rear View

FIGURE 5E

# Fluidic Throat Skewing Performance Envelope

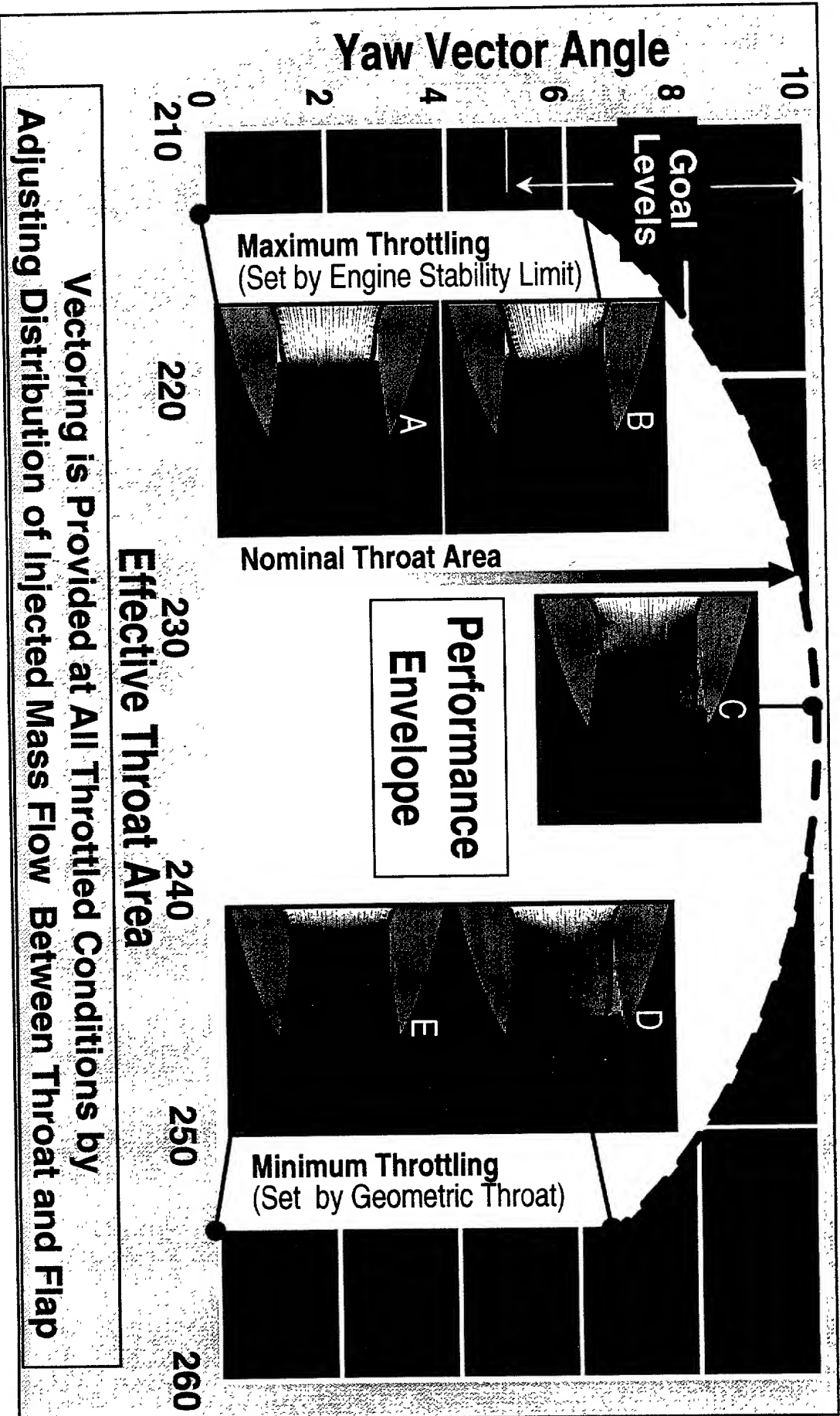


FIG. 6

LOCK1260-1  
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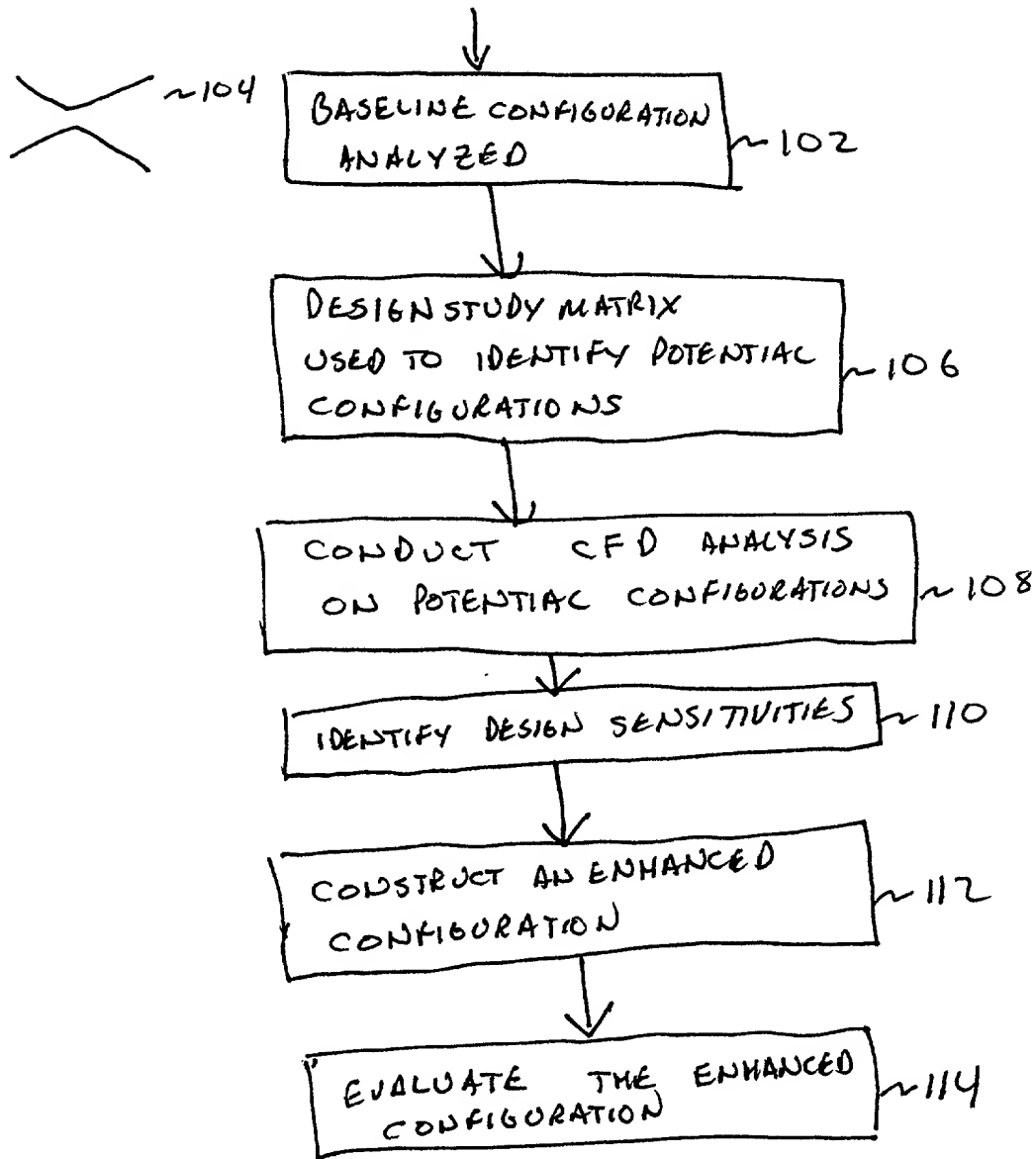
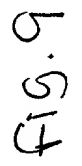
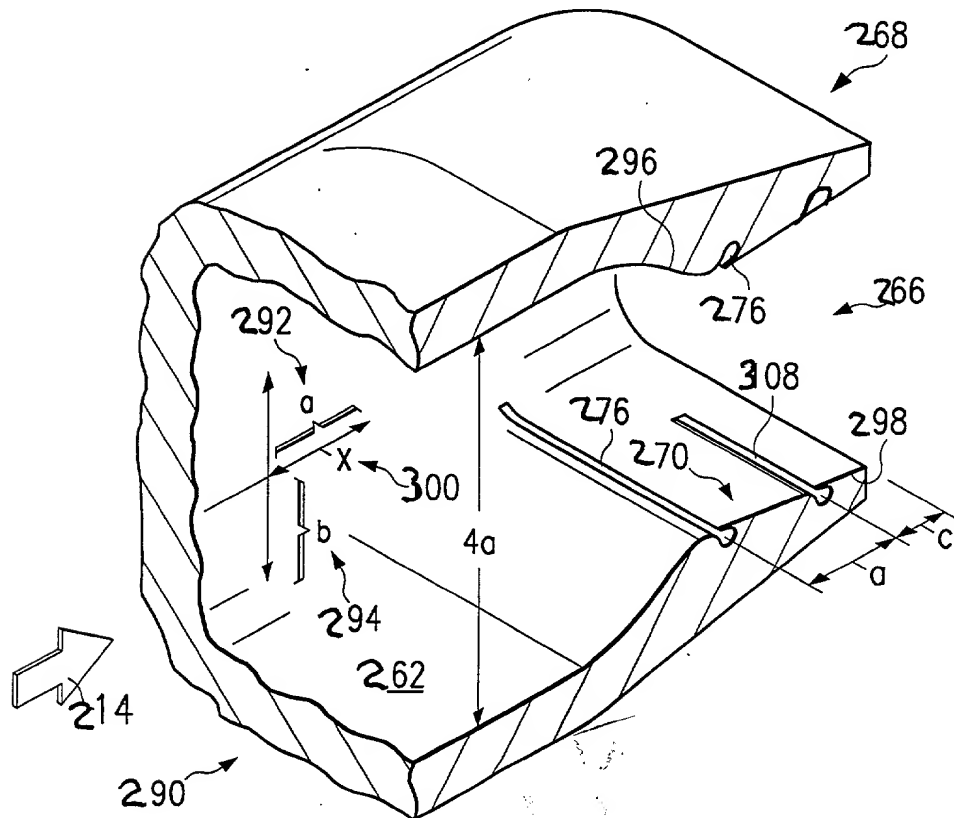


Fig. 7

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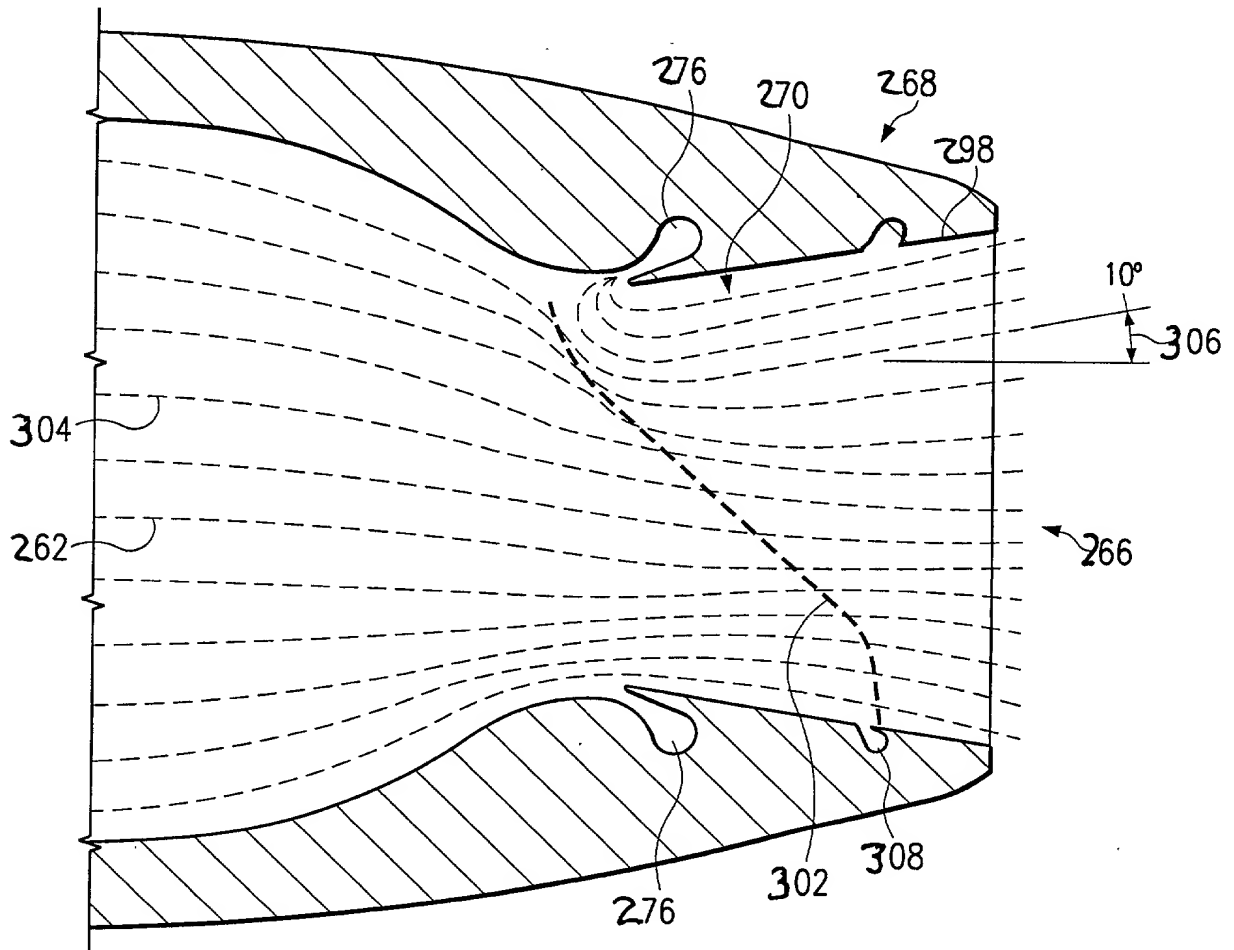


Fig. 12

**DECLARATION AND POWER OF ATTORNEY**  
**FOR PATENT APPLICATION**

**As the below-named inventor(s), I hereby declare that:**

My residence, post office address and citizenship are as stated below next to my name.

I believe I am the original, first and sole inventor (if plural, names are listed below) of the subject matter which is claimed and for which a patent is sought on the invention, design or discovery entitled **Method and Apparatus of Asymmetric Injection into Subsonic Flow of a High Aspect Ratio/Complex Geometry Nozzle**, the specification of which

X is attached hereto.

\_\_\_\_\_ was filed on \_\_\_\_\_ as Application Serial No. \_\_\_\_\_

I hereby state that I have reviewed and understand the contents of the above-identified specification, including the claims, as amended by any amendment(s) referred to above.

I acknowledge the duty to disclose information which is material to the examination of this application in accordance with Title 37, Code of Federal Regulations, Sec. 1.56(a).

I hereby declare that all statements made herein of our own knowledge are true and that all statements made on information and belief are believed to be true; and further that these statements were made with the knowledge that willful false statements and the like so made are punishable by fine or imprisonment, or both, under Section 1001 of Title 18 of the United States Code and that such willful false statements may jeopardize the validity of the application or any patent issued thereon.

I hereby appoint the following attorneys to prosecute this application and to transact all business in the Patent and Trademark Office connected therewith;

WILLIAM N. HULSEY III  
STEVEN R. SPRINKLE  
HAYWARD A. VERDUN

Registration No. 33,402  
 Registration No. 40,825  
 Registration No. 43,223

MARK L. BERRIER	Registration No. 35,066
ROBERT A. MCLAUCHLAN	Registration No. 44,924
ARMANDO PASTRANA, JR.	Registration No. 44,997
STEPHEN E. REITER	Registration No. 31,192
GREGORY P. RAYMER	Registration No. 36,647
DAVID F. KLEINSMITH	Registration No. 40,050
BARRY N. YOUNG	Registration No. 27,774
TIMOTHY W. LOHSE	Registration No. 35,255
STANLEY H. KIM	Registration No. 40,047
DARLENE W. HAYES	Registration No. 33,899
RAMSEY R. STEWART	Registration No. 38,322

All of the law firm of Gray Cary Ware & Freidenrich, LLP and

JOHN F. MCGOWAN

Registration No. 37,392

of Lockheed Martin Aeronautics Company

Direct all telephone calls to:

William N. Hulsey III  
Telephone: (512) 457-7040

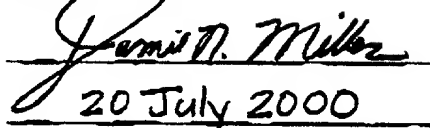
Address all correspondence to:

WILLIAM N. HULSEY III  
GRAY CARY WARE & FREIDENRICH, LLP  
100 Congress Avenue, Suite 1440  
Austin, Texas 78701

Full name of first inventor:

Daniel N. Miller

Inventor's signature:

  
20 July 2000

Date:

Residence (City, County, State)

Fort Worth, Tarrant, Texas

Citizenship:

United States of America

Post Office Address:

3252 Wabash Avenue  
Fort Worth, Texas 76109

Full name of second inventor:

Patrick J. Yagle

Inventor's signature:

Patrick J. Yagle

Date:

20 July 2000

Residence (City, County, State)

Fort Worth, Tarrant, Texas

Citizenship:

United States of America

Post Office Address:

3217 River Park Drive, Apt. 214  
Fort Worth, Texas 76116

Full name of third inventor:

Kerry B. Ginn

Inventor's signature:

Kerry B. Ginn

Date:

7-20-00

Residence (City, County, State)

Weatherford, Parker, Texas

Citizenship:

United States of America

Post Office Address:

402 Canyon Trail Road  
Weatherford, Texas 76087

Full name of fourth inventor:

Jeffrey W. Hamstra

Inventor's signature:

Jeffrey W. Hamstra

Date:

7/20/00

Residence (City, County, State)

Fort Worth, Tarrant, Texas

Citizenship:

United States of America

Post Office Address:

7004 Briarwild Court  
Fort Worth, Texas 76133